UNIVERSITY OF SOUTHERN CALIFORNIA
DEPARTMENT OF CIVIL ENGINEERING

RECORDING STRONG EARTHQUAKE MOTION – INSTRUMENTS, RECORDING STRATEGIES AND DATA PROCESSING

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ABSTRACT

This report describes the advances in recording of strong-motion. It emphasizes the amplitude and spatial resolution of recording starting with the first accelerographs, which had an optical recording dynamic range of about 50 dB, and a useful life longer than 30 years. When digital accelerographs started to become available in the late 1970s, their dynamic range increased progressively, and at present it is near 135 dB. However, most models have had a useful life shorter than 5 to 10 years. One benefit from a high dynamic range is early trigger and anticipated ability to compute permanent displacements. Another benefit is higher sensitivity and the possibility of recording smaller-amplitude motions (aftershocks, smaller local earthquakes and distant large earthquakes). The present trend of upgrading existing stations and adding new stations with high-dynamic-range accelerographs has lead to deployment of a relatively small number of new stations (the new high-dynamic-range digital instruments are 2 to 3 times more expensive than the old analog instruments or new digital instruments with a dynamic range of 60 dB or less). Thus the spatial resolution of recording, both of ground motion and structural response, has increased only slowly during the past 20 years — by a factor of about two. Future increase in the spatial resolution of recording will require orders of magnitude more funding for instruments and maintenance and for data retrieval, processing, management, and dissemination. This will become possible only with greatly less expensive and more "maintenance free" strong-motion accelerographs. In view of the rapid growth of computer technology, this does not seem to be out of our reach.

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1. INTRODUCTION

Strong-motion accelerograms properly interpreted are the nearest thing to scientific truth in earthquake engineering [1].

Full-scale experimental study in "earthquake engineering that is to have a sound scientific foundation must be based on accurate knowledge of the motions of the ground during destructive earthquakes. Such knowledge can be obtained only by actual measurements in the epicentral regions of strong earthquakes."…."typical seismological observations with their sensitive seismographs are not intended to make measurements in the epicentral regions of strong earthquakes"…. "Fundamentally different objectives of the engineer will require a basically different instrumentation than that needed for seismological studies. Such instrumentation must be designed, developed, installed and operated by earthquake engineers, who will be thoroughly familiar with the ultimate practical objectives of earthquake-resistant design." Today these statements made by Hudson[2] more than 30 years ago are still timely and relevant.

In the epicentral regions of strong earthquakes, damage to structures is caused by fault displacement, triggered landslides, large-scale soil settling, liquefaction, and lateral spreading, but the most widespread damage is caused by the strong shaking. To record the earthquake shaking of the ground and of structures, the U.S. Congress provided funds in 1932 that made it possible to undertake observations of strong-motion in California. The first strong ground motion was recorded on March 10, 1933 during the Long Beach, California, earthquake. The first strong-motion in a building was registered on October 2, 1933, in the Hollywood Storage Building, in Los Angeles, California. By 1934–35, all the important elements of a modern experimental earthquake engineering observation programs were in place: strong-motion observation,[3] analysis of records,[4] vibration observation in buildings, building and ground forced vibration testing,[5] and analysis of earthquake damage.[6]

By 1935, two dozen sites in California were equipped with strong-motion accelerographs (Fig. 1). Eight additional sites were instrumented with a Weed strong-motion seismograph.[3] By 1956, there were 61 strong-motion stations in the western U.S.[7] It is estimated that by 1963 about 100 strong-motion accelerographs were manufactured by the U.S. Coast and Geodetic Survey (USC&GS) and later by the U.S. Oceanographic Survey. By 1970, following the introduction of

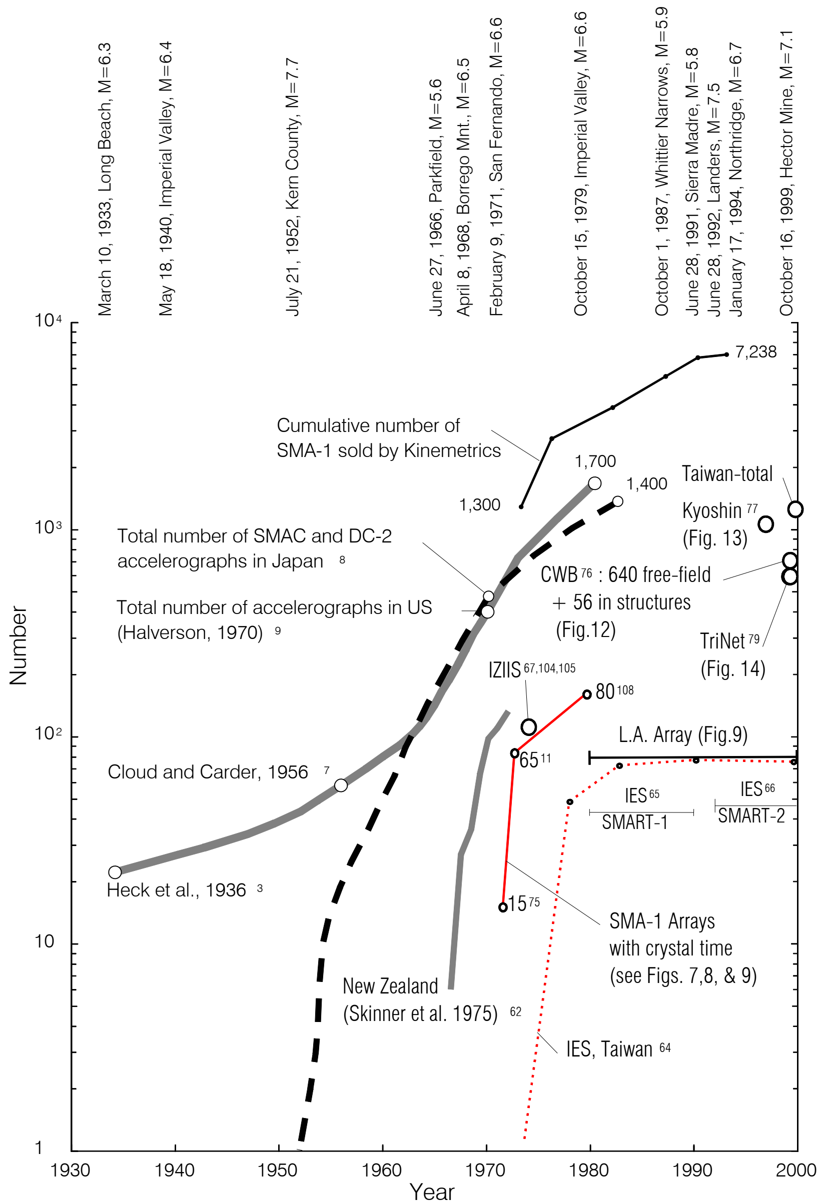

Fig. 1 Cumulative number of strong-motion accelerographs in California and in Japan up to 1980, of SMA-1 accelerographs sold worldwide, and of selected strong-motion projects in New Zealand and Taiwan. Selected California earthquakes contributing to the strong-motion database for southern California are also shown on the same time graph.

the AR-240 accelerograph, there were about 400 strong-motion instruments deployed in the western U.S. Strong-motion observation in Japan began in 1951,[8] and by 1970 there were 500 SMAC and DC-2 accelerographs in Japan.[9] As of the end of 1980, there were about 1,700 accelerographs in the United States (1,350 of those in California), and by January 1982 there were over 1,400 accelerographs in Japan (Fig. 1).

This report introduces selected aspects in the evolution of strong-motion programs trends in instrumentation development and in data processing, dissemination, and interpretation. Recent advances in the resolution of recorded amplitudes are contrasted with the neglect of the need to increase the spatial resolution of the recording networks. A comprehensive review of the subject is, however, beyond the scope of this work, which presents only a summary and an extension of earlier work by the author and Professor Todorovska on accelerographs, data processing, strong-motion arrays, and amplitude and spatial resolutions in recording. To clarify the recording needs, we will briefly address the modeling of structures, the role of full-scale versus laboratory experiments, and the priorities in experimental research in earthquake engineering.[10]

The topics covered are strong-motion instrumentation (Section 2), recording strong ground motion and the deployment of arrays (Section 3), recording strong-motion in buildings (Section 4), data processing (Section 5), and data storage and dissemination (Section 6).

2. STRONG-MOTION INSTRUMENTATION

This section reviews the developments in strong-motion accelerographs and their performance.

2.1 Development of Analog Strong-motion Recorders - Early Beginnings

Construction of accelerogrameters for the recording of strong-motion in destructive areas of major earthquakes has evolved from related work on seismological instruments.[12-16] Analyses of the magnification of displacements, of velocities, and of accelerations relative to the natural period of the instrument, have lead to the conclusion by Wenner[17] that “the records made by a very short-period and properly damped seismometer would give directly those components of the ground movement with which the structural engineer is most concerned, namely — the accelerations….” When U.S. Congress, in 1932, provided the funds to undertake observation of strong-motion in California, active development of instruments was initiated at National Bureau of Standards, the Massachusetts Institute of Technology, and the University of Virginia.

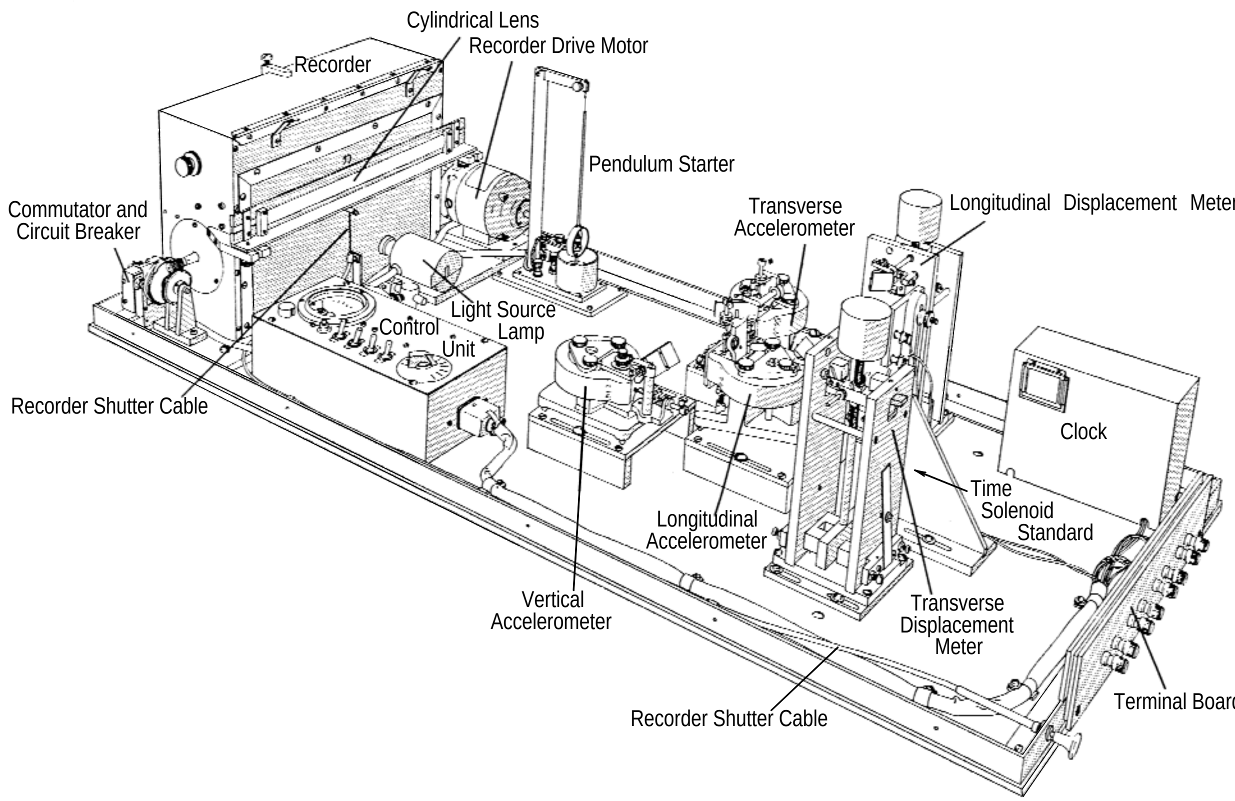

Fig. 2 USC&GS strong-motion seismograph.

The USC&GS standard accelerograph (the "original 6-inch accelerograph") was designed and equipped with three accelerometers having quadrifilar suspensions.[9,17,18] The later model was equipped with a 12-inch paper tape recorder, a pendulum starter, and pivot accelerometers (Fig. 2). Tests of these accelerographs on a shaking table are described in [18—20]. During the next 30 years, until the 1960s, these instruments provided most of the accelerograms recorded in free-field and in buildings (e.g., see Table 1 in [21]. Among the best-known examples are the Long Beach Public Utilities Building accelerogram that was recorded during Long Beach, California Earthquake of 1933,[22] and the El Centro accelerogram that was recorded during the Imperial Valley, California earthquake of 1940[23].

The first commercially available accelerograph, the AR-240, manufactured by Teledyne/Geotech in Texas, appeared in 1963.[9] It used photographic recording on 12-inch-wide photographic paper and it had light-tight film canisters that could be changed in daylight. This instrument recorded many important accelerograms, including those at Station No. 2, during the Parkfield, California earthquake of 1966,[24] and at Pacoima Dam during the San Fernando, California earthquake of 1971.[25] In Japan, the Strong-Motion Observation Committee developed two strong-motion instruments, the SMAC (models A,B,C,D, and E) and the DC-2. The first instruments were installed in 1952, and the first report presenting copies of the recorded accelerograms was published by the Strong-Motion Observation Committee in 1960.[26]

In 1967, Teledyne/Geotech introduced the RFT-250 accelerograph. It was smaller than the AR-240, recorded on 70-mm photographic film, and could operate on rechargeable batteries. Two horizontal and one vertical seismometers had transducer frequencies in the range from 19 to 20 Hz. Some models used seismometers with torsional wire, while others had a cross-spring pivot suspension. Starting was provided by an inverted pendulum, sensitive to tilt.

In 1970, Kinematics, then of San Gabriel, California, introduced the SMA-1 accelerograph, which also recorded on 70-mm film and had a vertical electromagnetic starter (VS-1). Before its production was discontinued in 1993, 7,238 units were sold all over the world (Fig. 1). So far, this instrument has produced, by far, the largest collection of analog strong-motion accelerograms.

Many detailed technical characteristics of the above instruments are summarized in [9]. Laboratory evaluation of the SMAC-B, the RFT-250, and the SMA-1 accelerographs, and evaluation of the vertical electromagnetic starter VS-1, are described in [27]. Photographs and descriptions of the USC&GS accelerograph and the Wenner accelerometer with pivot suspension, pendulum starter, and Weed seismograph can be found in [3]. Further pictures of the above and of additional, more modern instruments are presented in [28].

Seismological and strong-motion measurements may require use of a variety of devices with electrodynamic registration. The first systematic description of such devices was presented by Golitsyn.[29] Depending upon the application, the response of the coupled "transducer-galvanometer" system may be required to reproduce displacement, velocity, or acceleration of a moving point. By changing the constants of both devices, one can obtain a system with the transfer function that represents almost ideal displacement, velocity, or acceleration metering in a defined frequency band. "Almost ideal" means that the device has the ability to reproduce the amplitude of the motion of interest in the desired frequency band. However, the phase of the direct instrument output is distorted for all frequencies.[30]

The coupled transducer-galvanometer device has been popular in seismology and in earthquake engineering, and a great number of records were produced by such devices in different countries. For example, in the former Soviet Union structural vibrations were recorded with the help of multi-channel systems based on transducers such as VEGIK (Vibrograph, Electrodynamic, Geophysical Institute, Kirnos), SPM-16 (Seismotransducer, Mechanical), VBP (Vibrograph for Big Displacements), and galvanometers of the GB type.[31] Many seismologists have used the transducers VEGIK, SGK, and SKM with galvanometers of the GB type. A variety of techniques are used to control the response of these systems.[31,32] Strong-motion instruments used in China are often RDZ-type devices with galvanometers.[33]

There are certain advantages in using coupled systems as compared with single-degree-of-freedom devices: (1) the ability to get a broad range of amplifications, (2) the ability to separate recording and measuring locations, and (3) the ability to gather and write on the same medium (film, paper, magnetic tape) the response of several transducers attached at different places to the object being studied (this simplifies time matching of the different records). Thus, it is important to process the records obtained by such devices to be as representative of the ground (or structural) motion as possible and in as broad a frequency band as possible. This can be accomplished by careful digitization of these records and application of data processing and correction procedures.[30]

2.2 Other Strong-motion Recorders

Possibly the oldest instrument for detection of strong-motion is almost 1,900 years old. In 136 A.D., Chinese scientist Chôko designed a seismoscope that indicated direction of the first strong-motion pulse by the tipping of a vertical cylinder. The falling cylinder would then cause a ball to be released from the mouth of a dragon into the mouth of a waiting frog (Fig. 3). Depending upon the design, there were six or more dragon and frog pairs arranged in a circle, and it was assumed that the earthquake originated from the direction behind the dragon that dropped the ball.

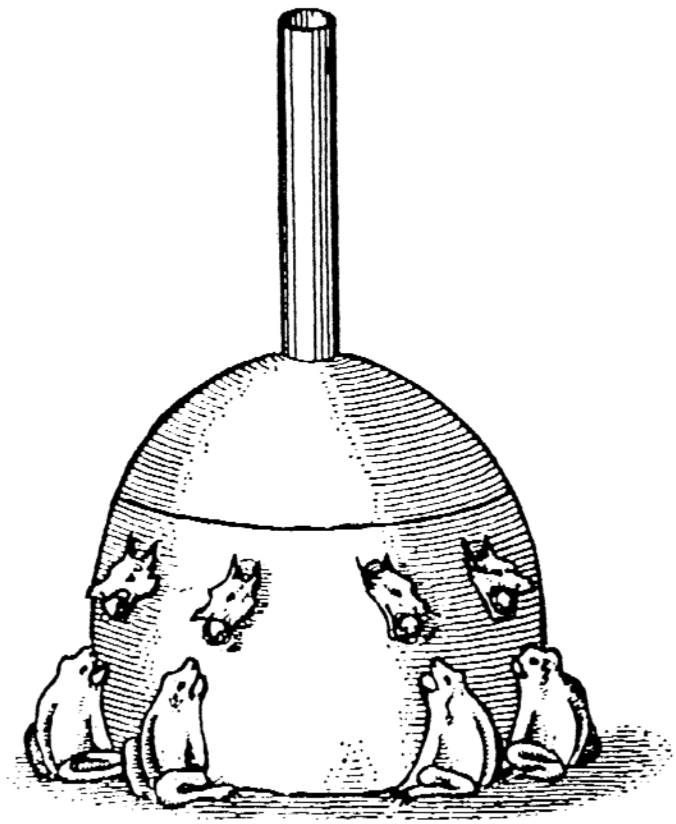

Fig. 3 Dragon seismoscope developed by Chinese philosopher/scientist Chôko in 136 A.D.

Early notable attempts to develop simple strong-motion recording instruments that would provide the structural engineer with information on response spectrum amplitudes were carried out by Golitsyn,[34] Kirkpatrick,[35] Suyehiro,[36,37] and the U.S. Coast and Geodetic Survey.[38] Based on these ideas and motivated by the need for simple and inexpensive strong-motion recorders, modern versions of the strong-motion seismoscope were developed and deployed in the U.S.S.R (the SBM Seismometer),[39,40] the United States (the Wilmot-type seismoscope),[41] and later in India[42] and several other countries,[43] with the largest concentrations being in the U.S. (400), Yugoslavia (320), and the U.S.S.R. (197).

The maximum response of the SBM seismometer provides one point on the relative displacement spectrum at natural period $T_n = 0.25$ s and for the fraction of critical damping $\zeta = 0.08$.[40] The Wilmot-type seismoscope provides the same at $T_n = 0.78$ s and for $0.06 < \zeta < 0.12$.[24,44]

During the past 45 years, numerous seismoscopes have registered strong ground motion. These measurements have been used to infer the overall response spectrum amplitudes[45] in order to study the variability of strong ground motion with distance from an earthquake source and site conditions,[46,47] to fill in the detailed information on strong ground motion where accelerographs have malfunctioned[24] or were not available,[48] to estimate earthquake magnitude and site intensity,[40,44,49] and to instrumentally relate similar intensity scales in different countries.[50]

Other peak recording devices have been developed, but their use in earthquake engineering has been short-lived and of limited value. An example is the Teledyne PRA-100 peak recording accelerograph, which recorded on a small piece of magnetic tape,[9] using the carrier erase principle. In 1969, its price was $225 — law compared with the lowest cost of contemporary accelerographs. Due to the increasing costs of labor, small volumes, the rapid decrease of the cost of electronic components, and the limited information provided by the peak recording devices, those recorders were gradually discontinued from earthquake engineering measurements of strong-motion.

2.3 Threshold Recording Levels of Strong-motion Accelerographs

Figure 4 shows a comparison of amplitudes of strong earthquake ground motion with the threshold recording levels of several models of strong-motion accelerographs. The weak continuous lines illustrate Fourier amplitude spectra of acceleration at 10 km epicentral distance, for magnitudes *M* = 1 to 7. The light gray zone highlights the frequency and amplitude ranges of recorded strong-motion, and the dark gray zone highlights the subset corresponding to destructive strong-motion. The heavier solid curve corresponds to typical destructive motions recorded in the San Fernando Valley of metropolitan Los Angeles during the 1994 Northridge,

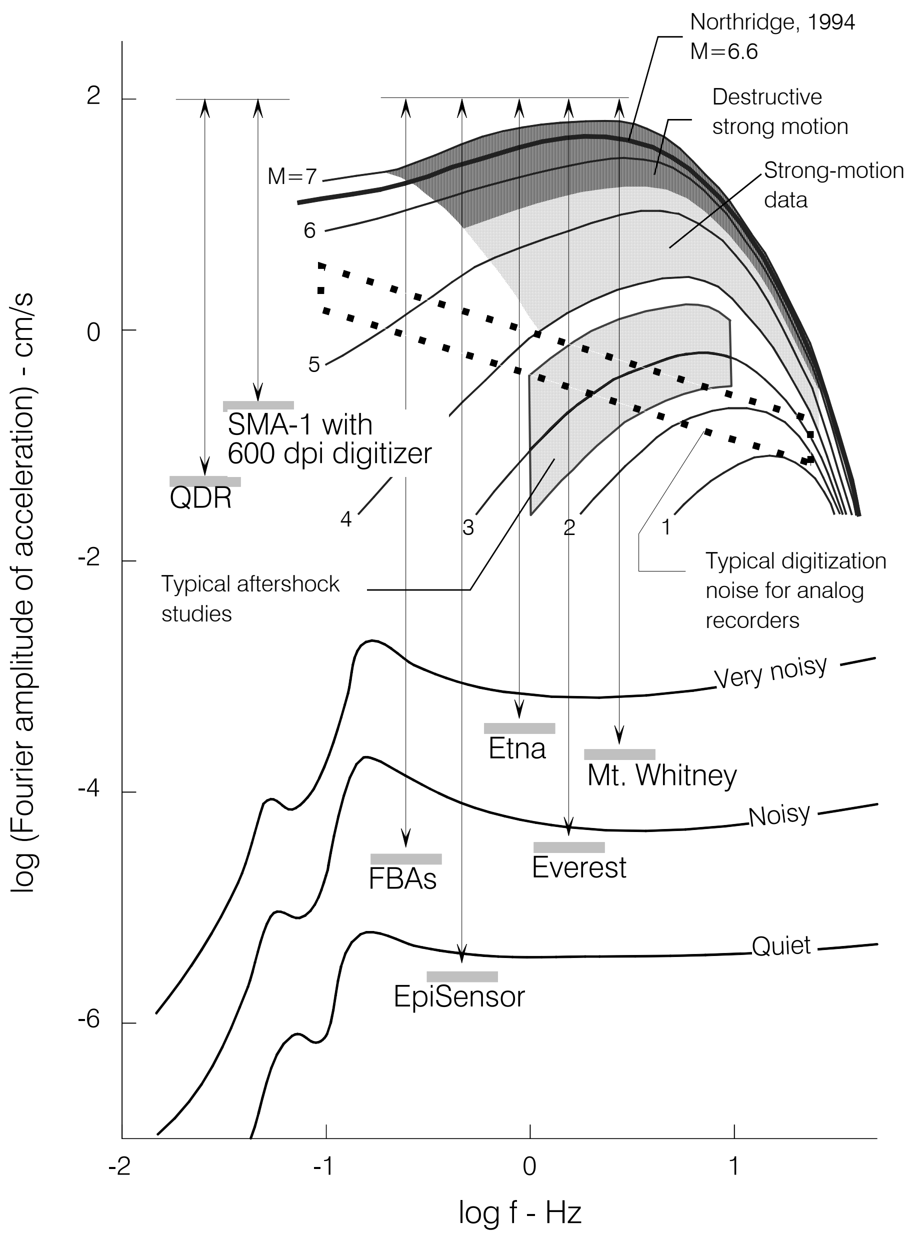

Fig. 4 Comparison of Fourier spectrum amplitudes of strong earthquake ground motion with those of typical aftershock studies and microtremor and microseism noise, threshold recording amplitudes of selected accelerographs, and typical digitization noise for analogue recorders.

California, earthquake. The lower gray zone corresponds to a typical range of seismological aftershock studies. The three continuous lines (labeled “Quiet,” “Noisy,” and “Very Noisy”) show spectra of microtremor and microseism noise some 5 orders of magnitude smaller than those of destructive strong-motion. The zone outlined by the dotted line shows typical amplitudes of digitization and processing noise for analog records. It also approximately describes a lower bound of triggering levels for most analog accelerographs. The shaded horizontal dashes represent the threshold recording levels for several accelerographs (SMA-1, QDR, ETNA, Mt. Whitney, and Everest, manufactured by Kinematics Inc.; http://www.kinemetrics.com) and transducers (FBA and EpiSensor).

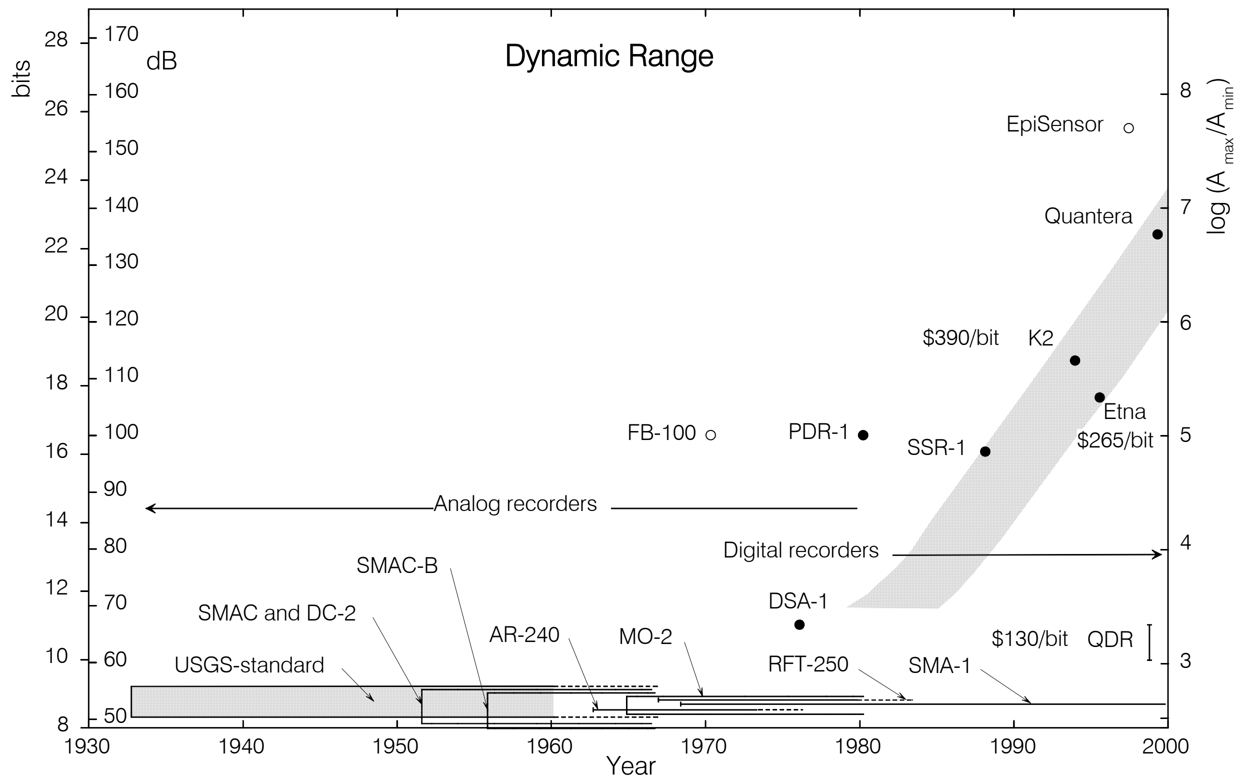

Fig. 5 Comparison of selected strong-motion accelerographs and digital recorders in terms of resolution (in bits), dynamic range in dB (= 20 log (A_{max}/A_{min})), and the ratio A_{max}/A_{min}, between 1930 and 2000.

In the late 1920s and the early 1930s, the amplitudes and frequencies associated with strong earthquake ground motion were not known. Considering this fact, the first strong-motion accelerographs were remarkably well designed.[3,9,51] During the first 50 years of the strong-motion program in the western U.S., all recordings were analog (on light-sensitive paper, or on 70-mm or 35-mm film). From the early 1930s to the early 1960s, most accelerograms were recorded by the USC&GS Standard Strong-motion Accelerograph (Fig. 2), including the famous 1933 Long Beach[3,22] and 1940 El Centro[23,52] accelerograms.

2.4 Dynamic Range of Strong-motion Accelerographs

The dynamic range of an analog strong-motion accelerograph (= 20 log (A_{max}/A_{min}), where A_{max} and A_{min} are the largest and smallest amplitudes that can be recorded) equals 40−55 dB and is

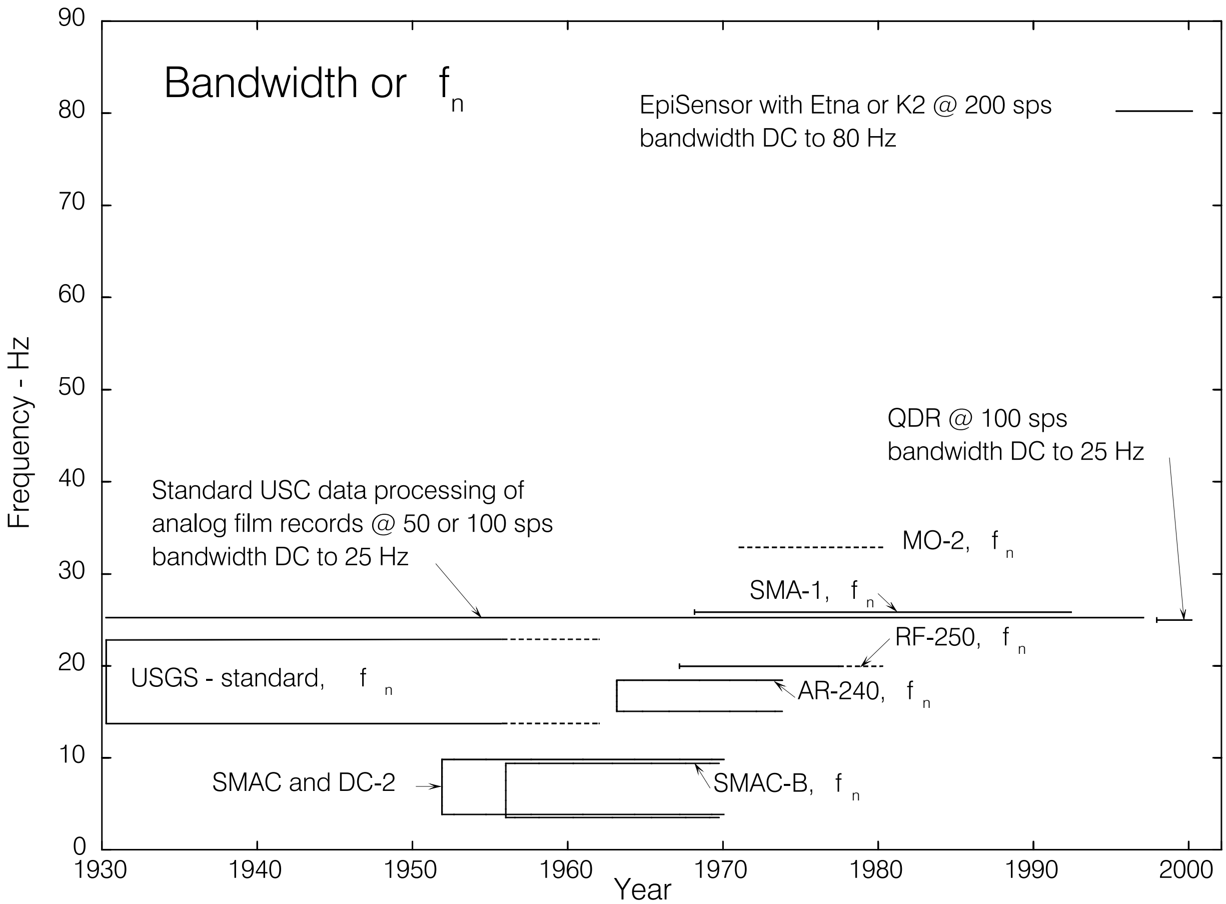

Fig. 6 Natural frequency, f_n, and useable bandwidth of commonly used strong-motion accelerographs between 1930 and 2000.

limited by the width of the recording paper or film, the thickness of the trace,[53] and the resolution of the digitizing system. If the digitizing system can resolve more than 5−6 intervals (pixels) per trace width, then the limit is imposed only by the thickness of the trace.[54] Between 1969 and 1971, with semi-automatic hand-operated digitizers, the dynamic range of the processed data was around 40 dB. In 1978, automatic digitizers, based on the Optronics rotating drum and pixel sizes of 50×50 microns were introduced.[55] For these systems, the amplitudes of digitization noise were smaller,[56,57] but the overall dynamic range representative of the final digitized data increased only to 50–55 dB (Fig. 5). By the late 1970s and the early 1980s, there was a rapid development of digital accelerographs due to several factors, including: (1) the advances in solid state technology and the commercial availability of many digital components for assembly of transducers and recording systems; (2) the increasing participation of seismologists in strong-motion observation, influenced by the successful use of digital instruments in local and global seismological networks; (3) the desire to eliminate the digitization step from data processing, because of its complexity and the requirement of specialized operator skills,[58] and (4) the expectation that by lowering the overall recording noise it would be possible to compute permanent ground displacements in the near field. At present, the modern digital recorders have dynamic ranges exceeding 135 dB. To avoid clutter, in Fig. 5 the growth of dynamic range with time is illustrated only for instruments manufactured by Kinematics Inc., of Pasadena, California. A summary of the instrument characteristics prior to 1970 can be found in the book chapters by Halverson,[9] and Hudson,[2,59] prior to 1979 in the monograph by Hudson,[51] and prior to 1992 in the paper by Diehl and Iwan.[60]

The transducer natural frequencies, f_n, and the useable bandwidths of the recorded data increased from about 10 Hz and 0–20 Hz, respectively, in the 1930s and 1940s to about 50 Hz and 0–80 Hz, respectively, at present (Fig. 6). For the modern digital instruments, the bandwidth is limited less by hardware and is chosen so that the useful information in the data, the sampling rate, and the volume of digital data to be stored are optimized.

In Fig. 5, the rate of growth in resolution and dynamic range is illustrated using six recorder-transducer systems manufactured by Kinematics Inc. The DSA-1 accelerograph, introduced in late 1970s, had a 66-dB digital cassette recorder with a 22-min recording capacity and a 2.56- or 5.12- s pre-event memory. In 1980, the PDR-1 digital event recorder was introduced, with 12-bit resolution and a 100-dB dynamic range using automatic gain ranging. The SSR-1, introduced in 1991, is a 16-bit recorder with a 90-dB dynamic range that can be used with FBA-23, (force balance accelerometer, 50 Hz natural frequency and damping 70% of critical), and with a 200-Hz sampling rate. The ETNA recorder (accelerograph) has 18-bit resolution and a 108-dB dynamic range, and the K2 recorder has 19-bit resolution and a 110-dB dynamic range. They were both introduced in 1990s and can accommodate force balance-type acceleration sensors (FBA or EpiSensor). Finally, the Quanterra Q330 is a broad-band, 24-bit digitizer with a dynamic range of 135 dB and a sampling rate up to 200 Hz. It can be used with real-time telemetry or can be linked to a local computer or recorder. The trend of rapidly increasing dynamic range began in 1980s.

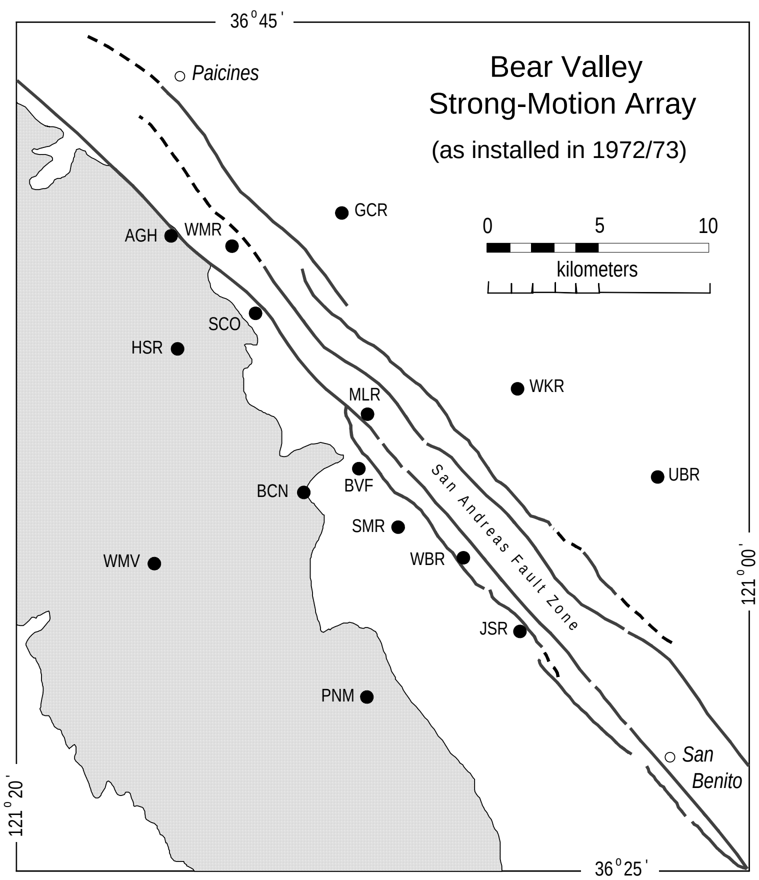

Fig. 7 Bear Valley Strong-Motion Array (the first strong-motion array with absolute radio time) as installed in 1972/73.

3. RECORDING STRONG GROUND MOTION

This section describes the developments in monitoring strong ground motion by arrays, guided by the need for source mechanism studies and by the observations of the damaging effects of earthquakes. The adequacy of the spatial resolution of strong-motion arrays will be discussed.

3.1 Deployment of Strong-motion Arrays

In the early stages of most strong-motion programs, the accelerographs are distributed in small numbers over vast areas, with density so low that often only one or two stations are placed in large cities or on important structures. For the situation in California prior to 1955 see Cloud and Carder,[7] and for Japan prior to 1952 see Takahashi.[8] In New Zealand the first strong-motion accelerographs were deployed in 1966 (Fig. 1; [61, 62]). In Taiwan, the installation of strong-motion accelerographs began in early 1970s.[63,64] By 1983, the Institute of Earth Sciences (IES) of Academia Sinica had 72 SMA-1 instruments, and by 1990 the number had grown to 79 (Fig. 1). Other strong-motion projects in Taiwan were SMART-1, a 43-station array in Lotung,[65] which opened in 1980 and closed at the end of 1990; the Lotung Large-Scale Seismic Test Array (LSST), constructed inside the SMART-1 Array, which opened in October of 1985 and closed in 1990; and the SMART-2 Array,[66] consisting of 45 Kinematics SSR-1 surface stations and two sets of downhole sub arrays, which opened in 1992. Since 1993, EPRI and Taipower have sponsored the Hualian Large Scale Seismic Test Array (HLSST) within the SMART-2 Array. In the former Yugoslavia, 100 SMA-I accelergraphs were deployed in 1975 by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje, Macedonia.[67]

At the beginning of most strong-motion programs (before the early 1970s) it was believed that "an absolute time scale is not needed for strong-motion work." However, for instrumentation in structures, "several accelerographs in the basement and upper floors of a building were connected together for common time marks… so that the starting pendulum that first starts will simultaneously start all instruments."[2,59]

Haskell's pioneering work[68] on near field displacements around a kinematic earthquake source provided a theoretical framework for solving the inverse problem — i.e. computing the distribution of slip on the fault surface from recorded strong-motion. The first papers dealing with this problem[69,70] showed the need for absolute trigger time in strong-motion accelerographs,[71-73] and for good azimuthal coverage, essentially surrounding the source with strong-motion instruments[74]. The first true array of strong-motion accelerographs, designed to record absolute time from a WWVB radio signal along the edge of 70-mm film, was deployed in 1972 in Bear Valley in central California.[75] It had 15 stations — 8 along the San Andreas fault and three on each side — between Paicines and San Benito (Fig. 7). The purpose of this array was to measure near field strong-motion using a small-aperture array (20 × 30 km). Since 1973, the Bear Valley array has recorded many earthquakes.

The source inversion studies of Trifunac and Udwadia[69,70] showed the uncertainties associated with inverting the dislocation velocity as a function of dislocation rise time and the assumed dislocation amplitudes. To reduce these uncertainties by direct measurement, it was decided that active faults in Southern California should be instrumented with strong-motion accelerographs. To this end, and to provide adequate linear resolution that would allow following the dislocation spreading along the surface expression of the fault, we installed the San Jacinto Strong-motion Array in 1973/74 (Fig. 8). This was the first linear (along the fault) strong-motion array. As with

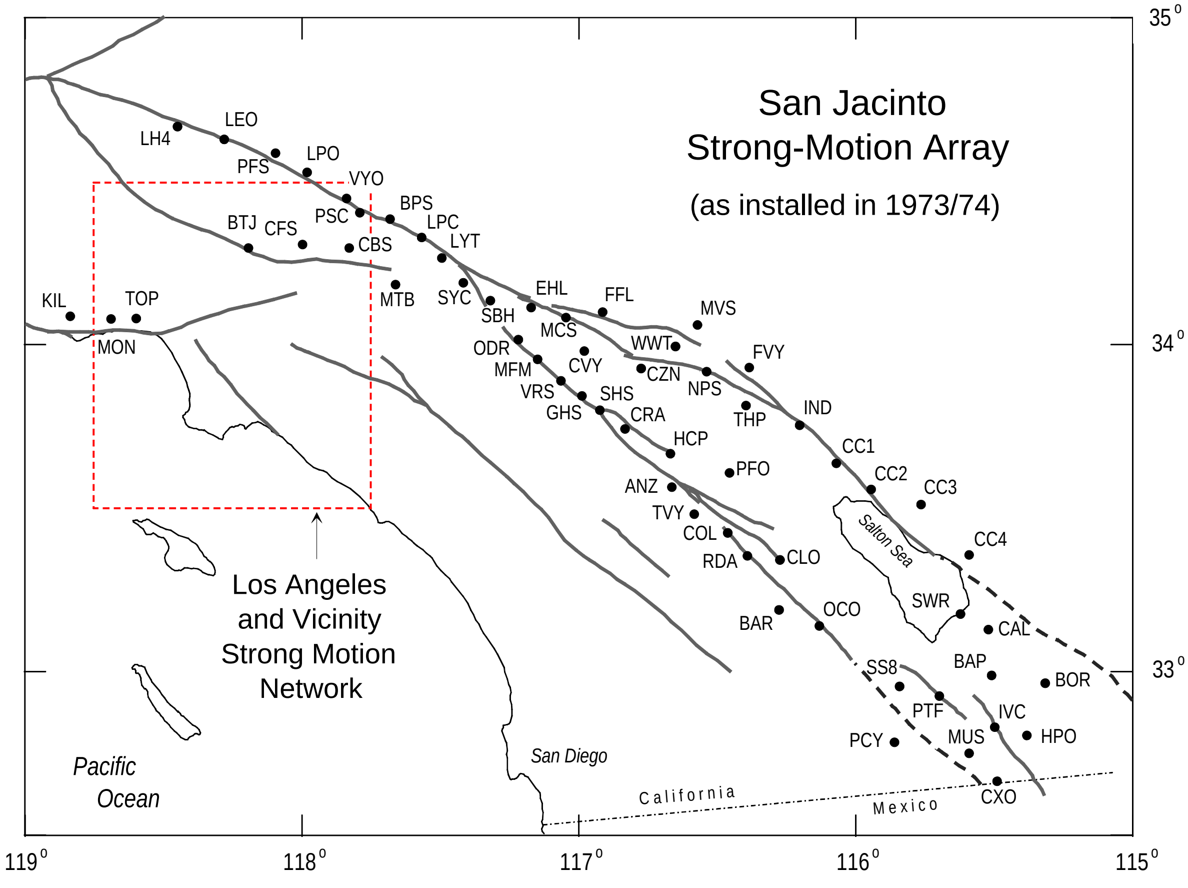

Fig. 8 Stations of the San Jacinto Array (solid dots) and the Los Angeles and Vicinity Strong-Motion Network (see Fig. 9) as installed in 1973/74 and in 1979/80, respectively.

Bear Valley Array a WWVB radio signal was used to write absolute time along the edge of 70-mm film. So far, it has not recorded a propagating dislocation, because there has not been such an earthquake on the San Jacinto fault since 1974. This array was very successful, nevertheless.

It recorded strong-motion from numerous earthquakes in the highly seismically active area surrounding the array.

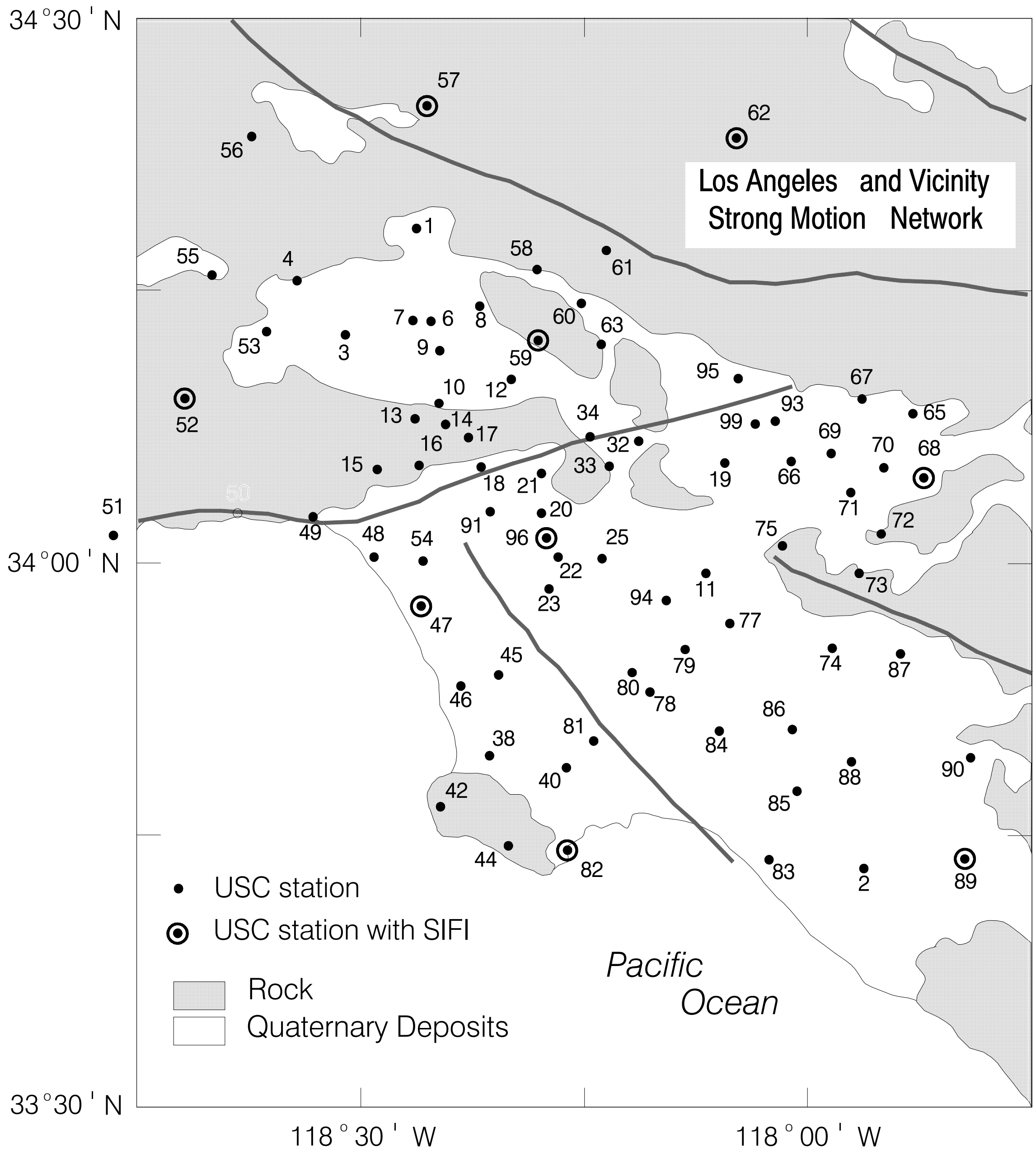

Fig. 9 Los Angeles and Vicinity Strong-motion Network (operated by USC). All stations are in small or one-storey buildings (i.e., approximately in "free field").

In 1979/80, the Los Angeles and Vicinity Strong-motion Network (Fig. 9) was installed to link the San Jacinto Array (Fig. 8) with the strong-motion stations in many tall buildings in central Los Angeles (Figs. 10, 11). This also constituted our first attempt to find out what could be learned from a large two-dimensional surface array with spatial resolution of 5 to 10 km.

Between 1987 (the Whittier Narrows earthquake) and 1999 (the Hector Mine earthquake), this network contributed invaluable strong-motion data (about 1,500 three component records; see http://www.usc.edu/dept/civil_eng/Earthquake_eng/), which will be studied by earthquake engineering researchers for many years to come.

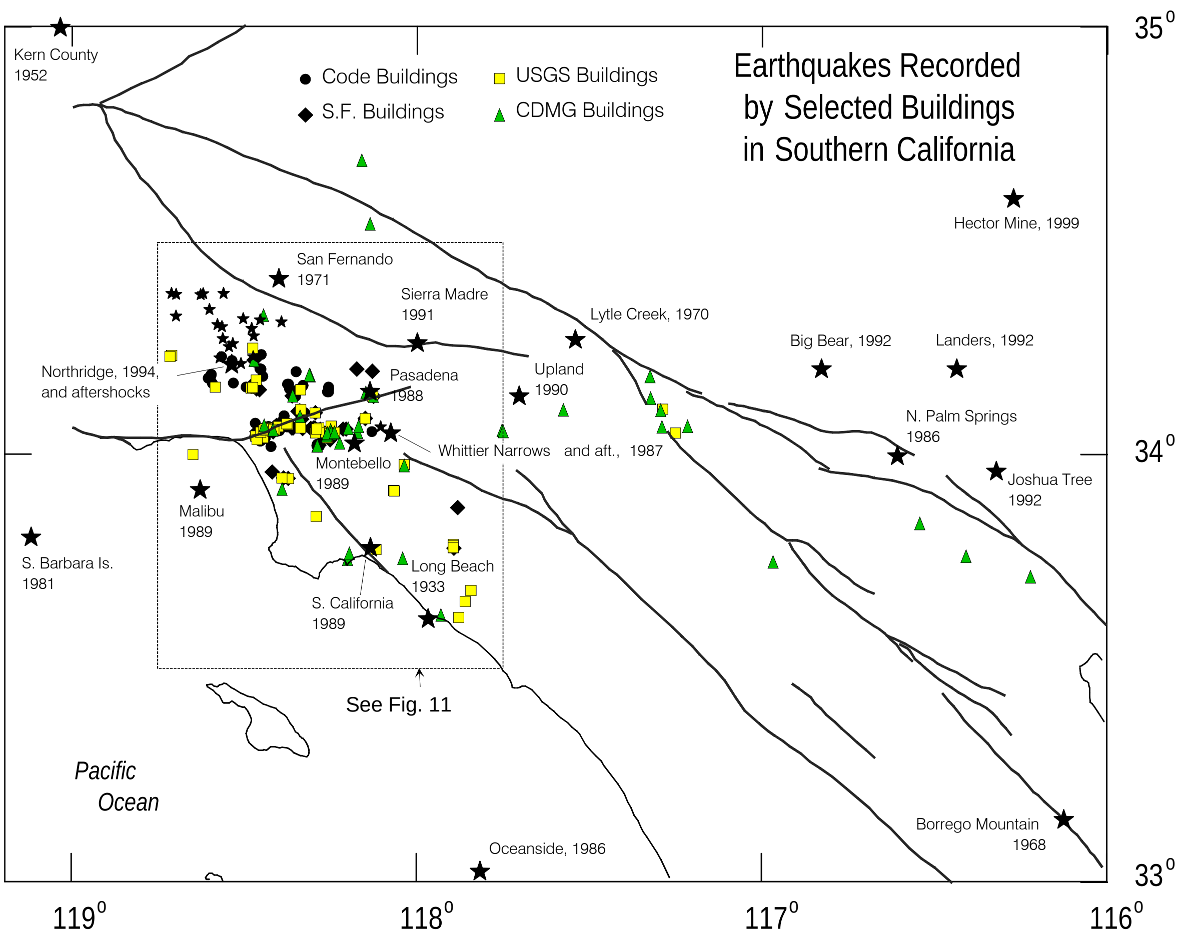

Fig. 10 Larger earthquakes recorded by accelerographs in buildings in Southern California.

In the late 1980s, Y.B. Tsai of National Central University in Taiwan proposed an extensive strong-motion instrumentation program called the Taiwan Strong-Motion Instrument Program

(TSMIP), which was organized by the Central Weather Bureau (CWB) and implemented between 1991 and 1996 (Fig. 12). By the end of 2000, a total of 640 free-field accelerographs and 56 structural arrays had been deployed. This array consists of 46 Teledyne A-800

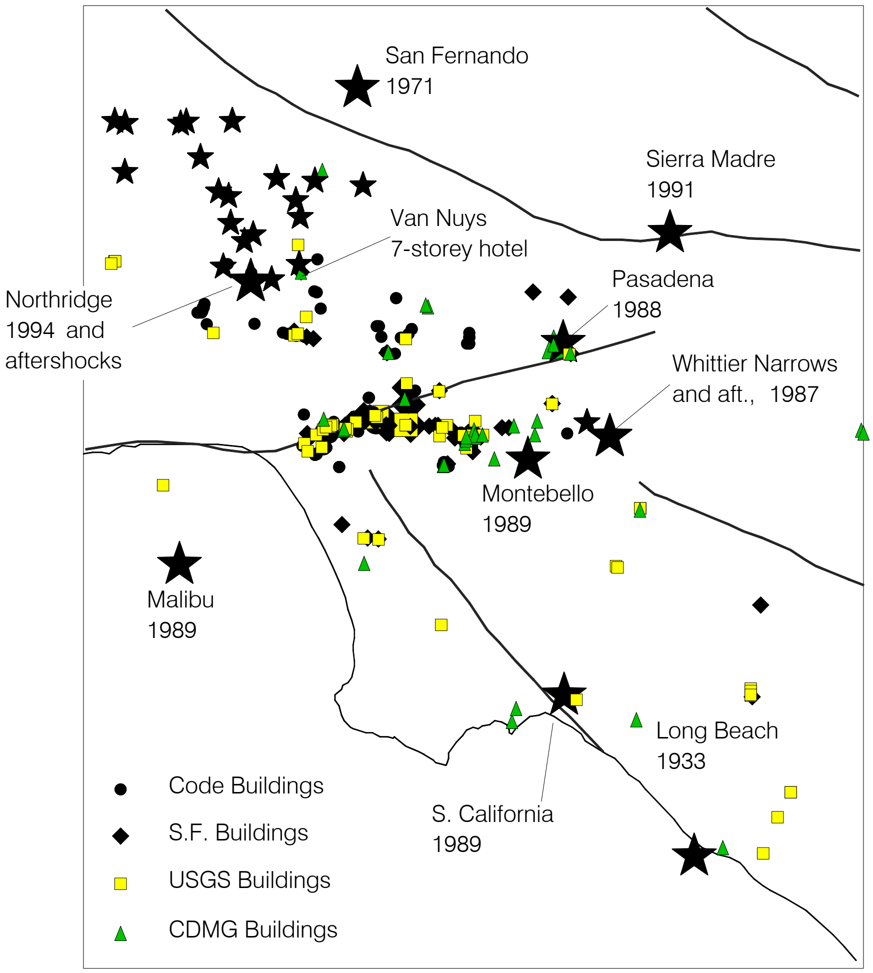

Fig. 11 An enlargement of the rectangular window in Fig. 10 (Los Angeles metropolitan area).

accelerographs (12-bit, resolution), 393 Teledyne A-900 accelerographs (16-bit, resolution), 163 Terratech IDS and IDSA accelerographs (16-bit resolution), and 38 Kinematics ETNA and K2 accelerograph (18-bit, and 24-bit respectively).[76] The 56 structural arrays are multi-channel (32 or 64 channels) with central recording.

On September 20, 1999, the Chi-Chi, M_w = 7.6, earthquake occurred. The main shock produced 441 digital strong-motion records. At the time of the earthquake there were 640 accelerographs

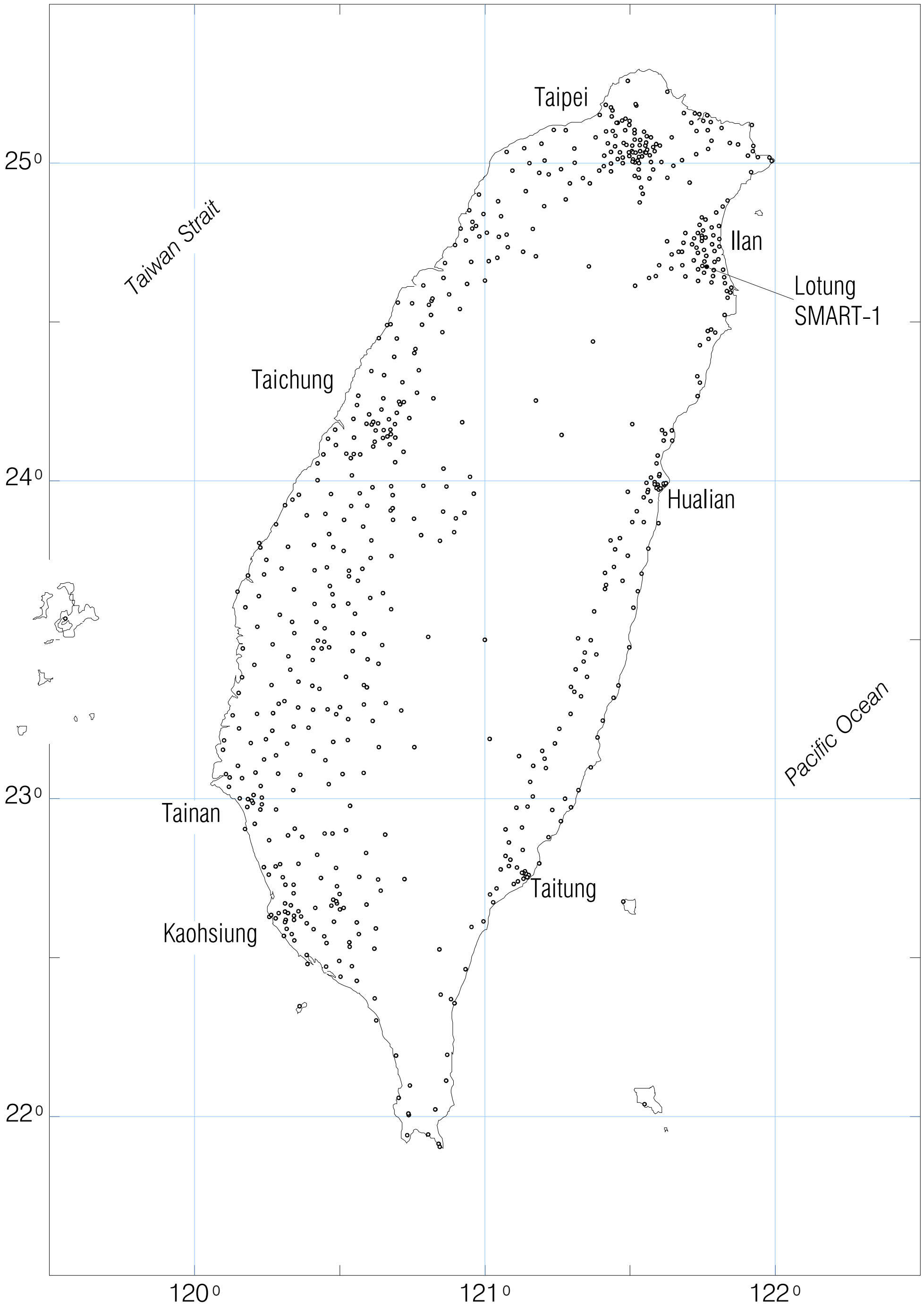

Fig. 12 Central Weather Bureau (CWB) free-field, three-component, digital accelerograph stations of the Taiwan Strong-Motion Instrumentation Program (TSMIP).

at free-field sites, but 199 (31%) did not record. There were also 55 strong-motion arrays in buildings and on bridges, 35 of those recorded the main shock. This was the most successful recording ever of strong-motion during a major earthquake[76].

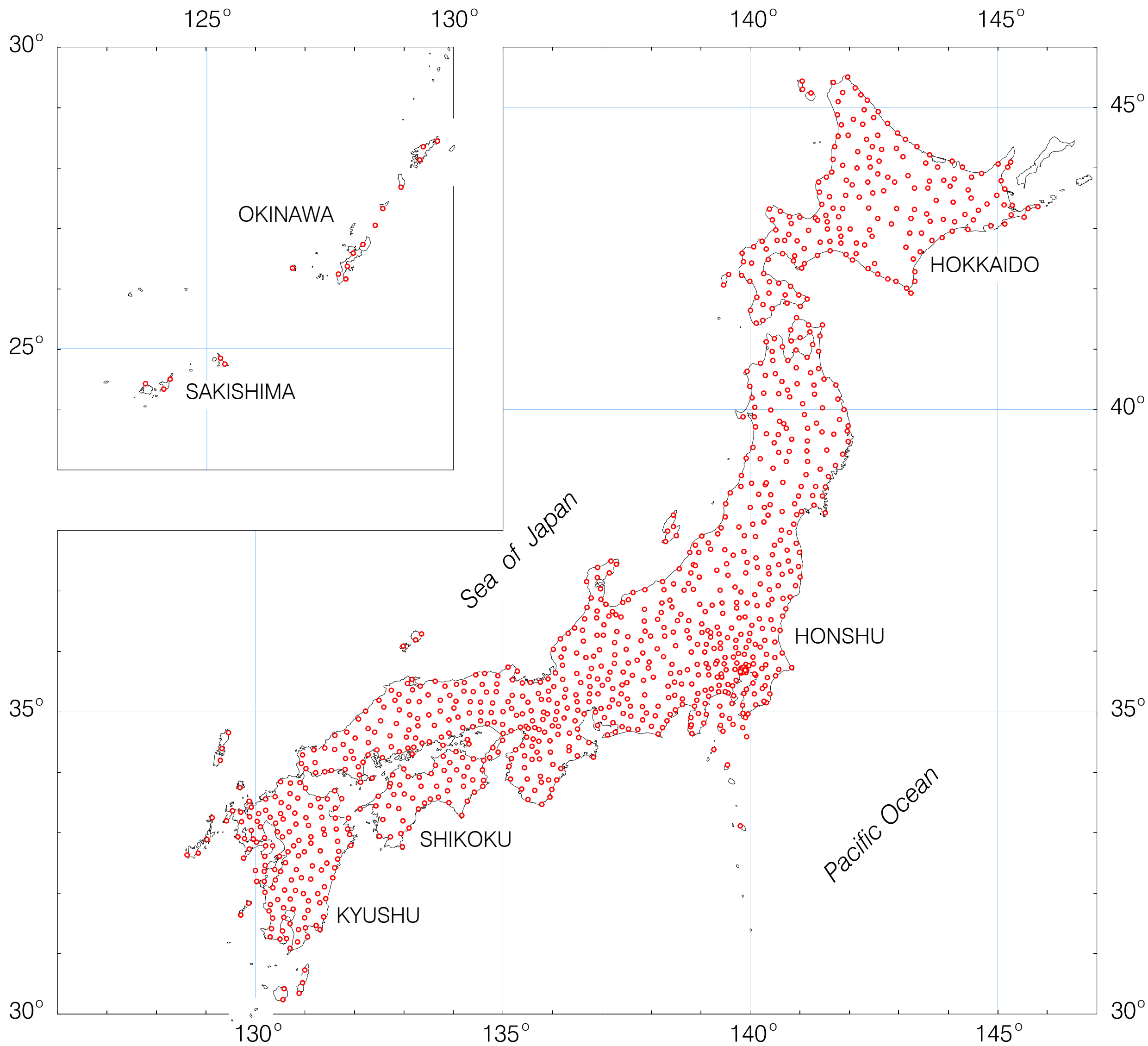

Fig. 13 Kyoshin-Net strong-motion stations.

Following Kobe (Hyogoken-nanbu) earthquake in 1995 in Japan, the National Research Institute for Earth Science and Disaster Prevention (NIED) of the Science and Technology Agency was given the responsibility by the Japanese government to implement a strong-motion observation program. The Kyoshin Net (K-NET) was implemented during the following year[77] and now consists of 1,000 strong-motion observation stations, a control center, and two mirror sites of the control center. It uses K-NET95 seismographs manufactured by Akashi Co., with characteristics similar to the Kinematics K2. The sensor V403BT is a tri-axial force-balance accelerometer,

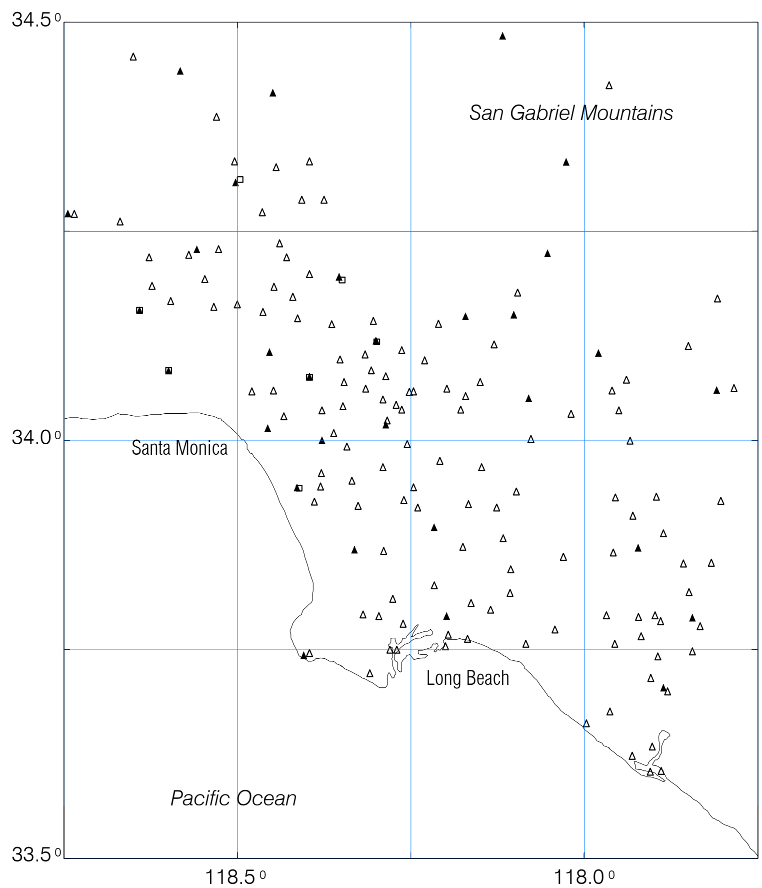

Fig. 14 TriNet strong-motion stations in the Los Angeles area (SCSN/TriNet station—solid triangles; CSMIP/TriNet stations—open triangles; NSMIP/TriNet stations—open squares)

with a natural frequency of 450 Hz and a damping factor of 0.707. The A/D converter is a 24-bit type, with a clock frequency of 1.64 MHz. The average station-to-station distance is about 25 km. This spacing has been designed to sample the epicentral region of an earthquake with magnitude 7 or larger anywhere in Japan (Fig. 13).

Following the Landers (1992) and Northridge (1994) earthquakes in California, plans for an improved instrumentation network to capture data from large and damaging earthquakes were initiated by the United States Geological Survey (USGS), California Institute of Technology, and the California Division of Mines and Geology (CMDG). Called TriNet, this partnership aims to coordinate the broadband and strong-motion recording networks into one system.[78] In addition to having dense spacing, TriNet will aim to determine an earthquake's magnitude and its hypocenter within a minute of the event and to disseminate maps showing the distribution of peak velocities for moderate and large events within 3 minutes.[79] In Sacramento, California, CDMG will process, near real-time, data from 400 strong-motion stations. Caltech and USGS in Pasadena will process in real-time data from 150 broad-band and strong-motion stations and from 50-strong-motion stations. Figure 14 shows the TriNet stations in the greater Los Angeles area.

Comprehensive review of many other strong-motion networks and of the distribution of accelerographs world wide is beyond the scope of this work, but readers may peruse example papers on these subjects for Argentia,[80] Bulgaria,[81] Canada,[82] Chile,[83] El Salvador,[84] Greece,[85] India,[86-88] Italy,[89] Japan,[90-92] Mexico,[93] New Zealand,[94-97] Switzerland,[98] Taiwan,[99] Venezuela,[100] and the former Yugoslavia.[67] A useful older review of the worldwide distribution of accelerographs can be found in the paper by Knudson.[101]

3.2 Adequacy of the Spatial Resolution of Strong-motion Arrays

By comparing the spatial variability of observed damage with the density of strong-motion stations during the 1994 Northridge earthquake, in Fig. 15 we illustrate the need for a higher density of observation stations then currently exists. The spatial variability of amplitudes of strong ground motion results from (1) the differences along the paths traveled by the strong-motion waves and (2) variations in the local site conditions. By recording the motion with dense arrays, this variability can be mapped for each contributing earthquake. Then, by some generalized inverse approach, and assuming a physical model, the results can be inverted to determine the causes of the observed differences and to further test and improve the assumed models and their forward prediction capabilities.

In analyses of strong-motion recordings of different earthquakes at the same station, it is sometimes assumed that the local site conditions are "common" to all the recorded events and that only the variations in propagation paths contribute to the observed differences in the recorded spectra. It can be shown, however, that *the transfer functions of site response* for two-

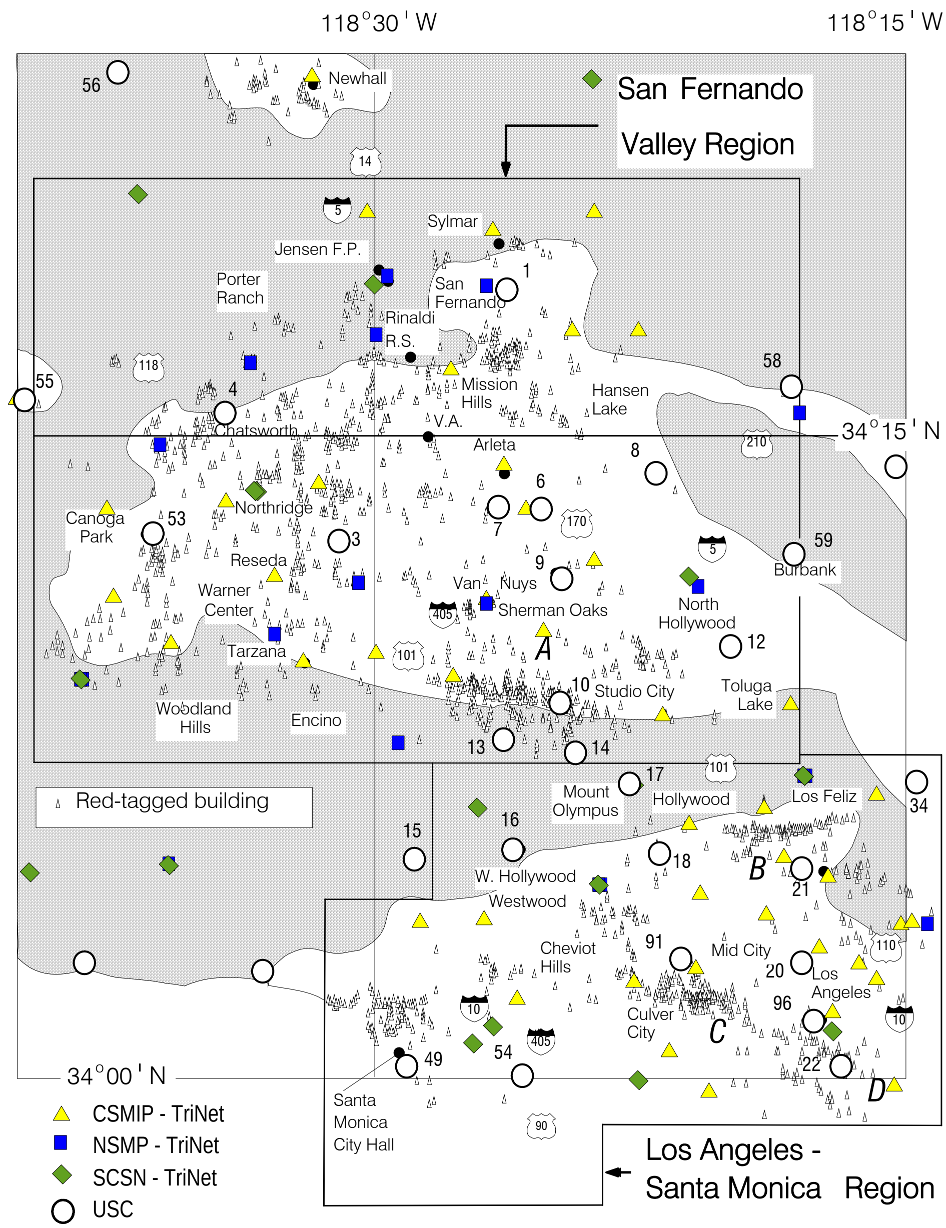

Fig. 15 Distribution of damaged (red-tagged) buildings in the San Fernando Valley and the Los Angeles—Santa Monica area following the 1994 Northridge earthquake (small triangles) and of the USC and TriNet (current and future) strong-motion stations (different larger symbols).

and three-dimensional site models *depend upon the azimuth and incident angles of strong-motion waves,*[102] so that theoretically calculated or empirically determined spectral peaks in the site-specific response are not always excited.[103-105] In view of the fact that the analyses of re-occurring characteristics of site response can be carried out at any strong-motion station where

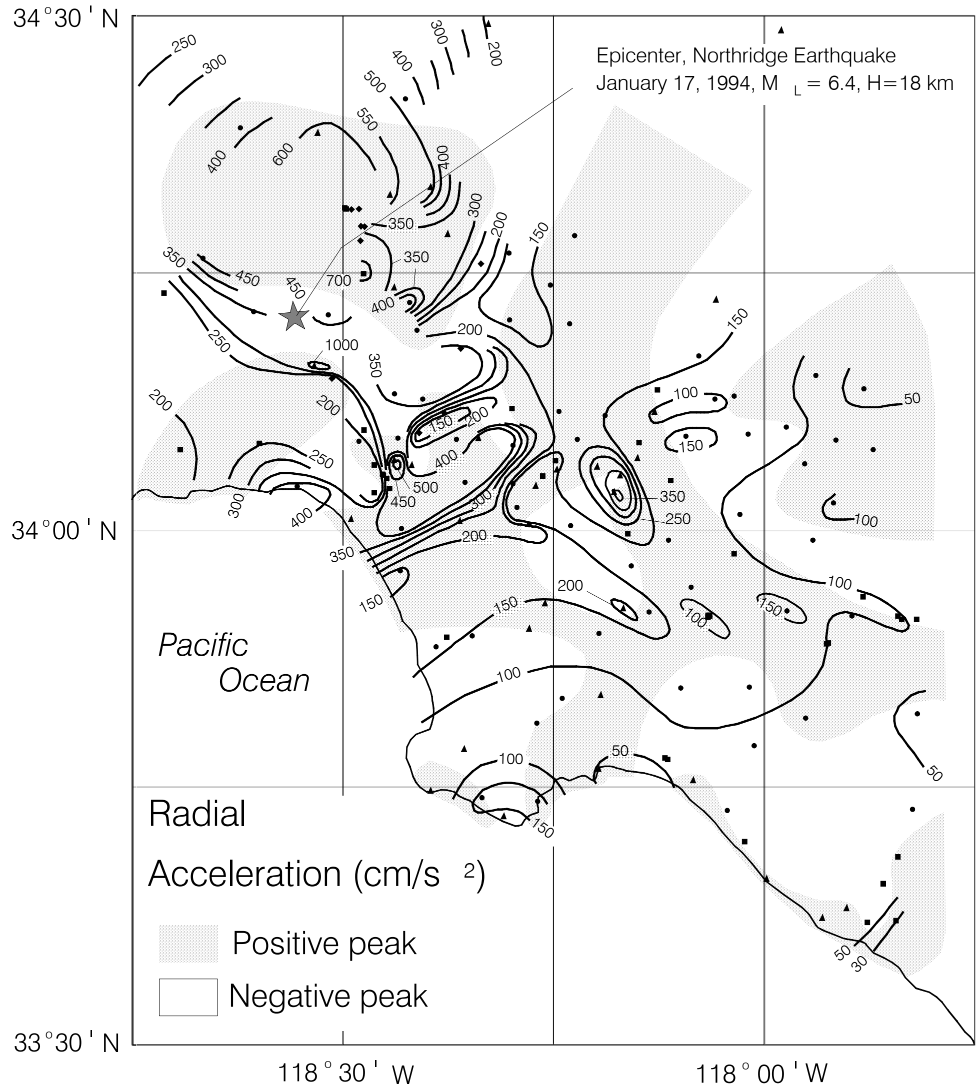

Fig. 16 Contour plot of peak (corrected) ground acceleration (in cm/s^2) for the radial component of motion recorded in metropolitan Los Angeles during the 1994 Northridge earthquake. The shaded region indicates areas where the largest peak has a positive sign.

multiple records are available, analyses of such recordings should be performed prior to the design and deployment of dense strong-motion arrays, so that the findings can be used in the design of future dense strong-motion arrays. Unfortunately, only isolated studies of this type can be carried out at present,[103-105] because the agencies archiving and processing strong-motion data usually do not digitize and process strong-motion data from aftershocks. Also, it should be clear

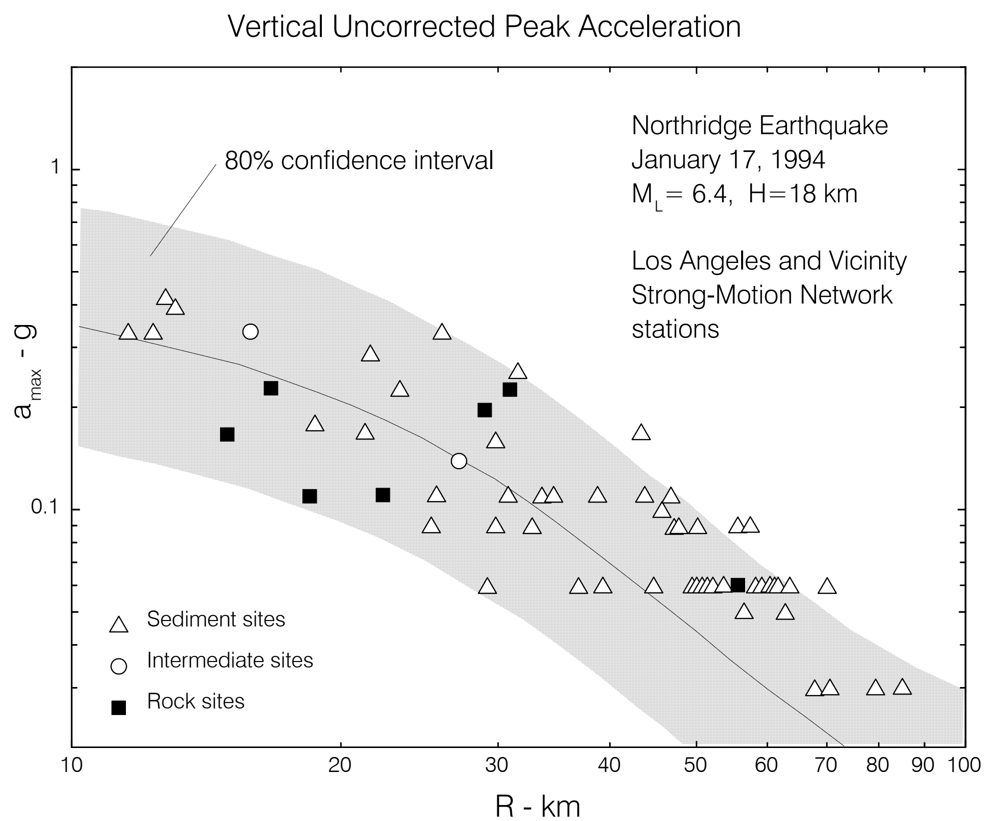

Fig. 17 Uncorrected peak ground accelerations (vertical component) recorded by 63 stations of the Los Angeles Strong-Motion Network (the triangular, square and circular symbols) during the Northridge, California, earthquake of 17 January, 1994, and the average trend (the solid line) and 80% confidence interval predicted by the regression model.

from the above discussion that strong-motion stations (in free-field or in the structure) should not be "abandoned" when the instruments become obsolete or because of changes in the code or in the organization responsible for maintenance and data collection and archiving. *Stations that have already recorded numerous earthquakes are particularly valuable, and their continued operation and maintenance should be a high priority.*

Detailed studies and new research and interpretation of strong shaking from the 1994 Northridge earthquake are yet to be carried out and published. So far, most effort has been devoted to data preservation and to only general and elementary description of the observed earthquake effects.[106-124] Nevertheless, several important observations have already emerged from the above studies. The first is that *the density of the existing strong-motion stations is not adequate to properly describe the spatial variations of the damaging nature of strong-motion*, and the second one is that the *spatial variation of spectral amplitudes, and of peak motion amplitudes and their polarity, indicate "coherent" motions* (i.e., slowly varying peak amplitudes and polarities of the

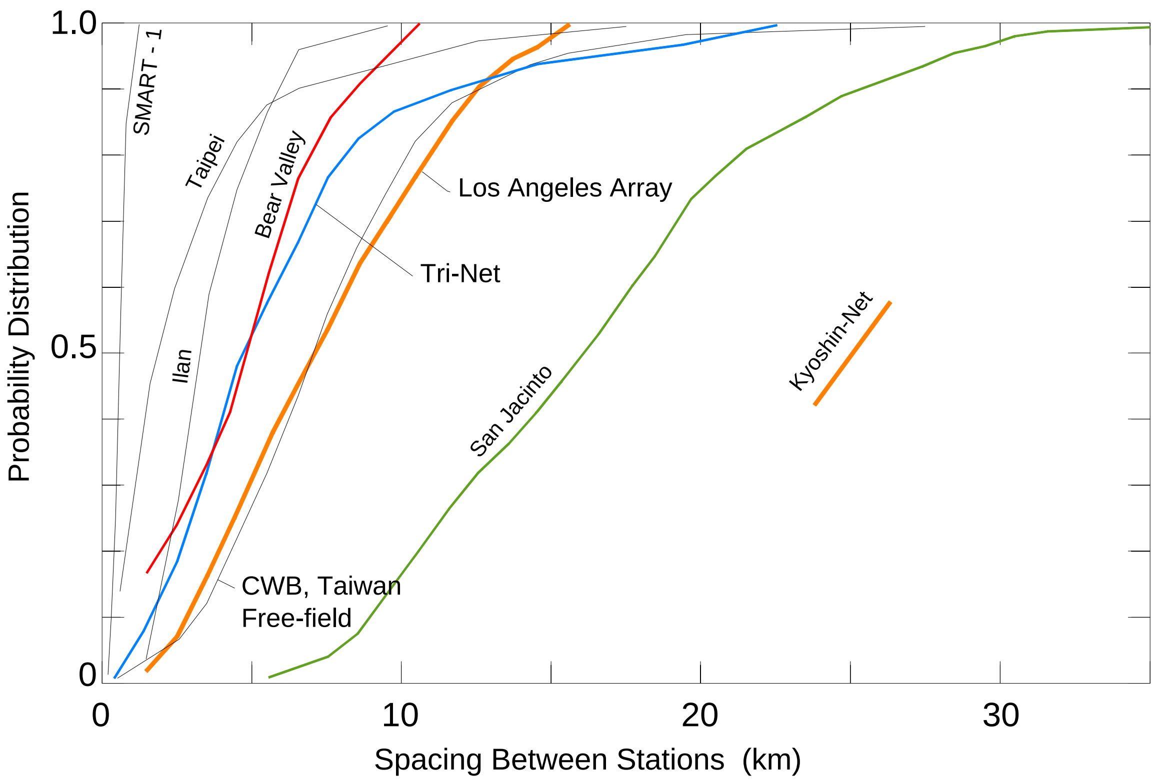

Fig. 18 Distribution of station-to-station distances (km) for selected strong-motion arrays. SMART-1 array was located in Lotung, in the area of Ilan. Taipei and Ilan are in the northern part of Taiwan (see Fig. 12). The Bear Valley, TriNet, CWB, Los Angeles and San Jacinto networks are shown in Figs. 7, 14, 12, 9, and 8, respectively.

largest peaks) over distances on the order of 2 to 5 km, even for "short" waves, associated with peak accelerations (Fig. 16). This suggests *that the large scatter in the empirical scaling equations of peak amplitudes* (e.g. see Fig. 17) *or of spectral amplitudes of strong-motion may be associated in part with sparse sampling over different azimuths*. It was further found that *the nonlinear response of soils, for peak velocities larger than 5 to 10 cm/s, begins to interfere with* *linear site amplification patterns and that for peak velocities in excess of 30–40 cm/s it completely alters and masks the linear transfer functions determined from small and linear motions at the same stations.*[117,118]

The adequacy of spatial resolution of strong-motion arrays can be also viewed in terms of the wavelengths that govern the problem being analyzed. In engineering applications, frequencies near 25 Hz are near the high-frequency end of the used spectral range of strong-motion. Assuming that a typical soil may have a shear wave velocity in the range 100 to 300 m/s, the associated wavelengths are 4 to 12 m, and measuring this motion requires station spacing on the order of meters. Budget constraints may not allow such dense arrays except in special-purpose studies of highly localized phenomena. Frequencies where the Fourier amplitude spectrum of strong motion peaks are near 1 Hz (Fig. 4). Thus, to resolve the wavelengths of strong-motion (300 m to 1000 m long), which carry most of the energy, the station spacing would have to be on the order of 100 m or less.

Table 1 Average station-to-station spacing of selected strong-motion accelerograph arrays (Fig. 18)

Array	Average station-to-station Spacing (km)
SMART-1 (Fig. 12)	0.5
TAIPEI (Fig. 12)	1.8
Ilan (Fig. 12)	3.3
Tri-Net (Fig. 14)	4.7
Bear Valley (Fig. 7)	4.8
CWB-TSMIP, free field (Fig. 12)	7.0
Los Angeles and Vicinity (Fig. 9)	7.1
San Jacinto (Fig. 8)	16.0
Kyoshin-Net (Fig. 13)	25.0

Figure 18 shows the distribution of station-to-station spacing for some of the arrays mentioned above. Table 1 illustrates the average station-to-station distances. Except for the former SMART-1 array, it is seen that no array in the remaining eight examples has small-enough inter-station spacing to resolve even the wavelengths associated with peak amplitudes of strong-motion acceleration spectra. In Fig. 19, to illustrate the relative densities of some of the above-discussed arrays, the central part of Honshu Island (Japan), Taiwan, and Southern California are plotted using the same scales. As already seen in Fig. 18 and Table 1, at present Taiwan's CWB TSMIP network has the highest density of strong-motion stations.

3.3 Cost

Figure 20 shows the cost of one self-contained, tri-axial accelerograph. The lower curves show the cost at the time of production. The top curves show approximate cost, corrected for inflation, in terms of the value of $US in 2000. The cost of the USC&GS standard accelerograph (Fig. 2),

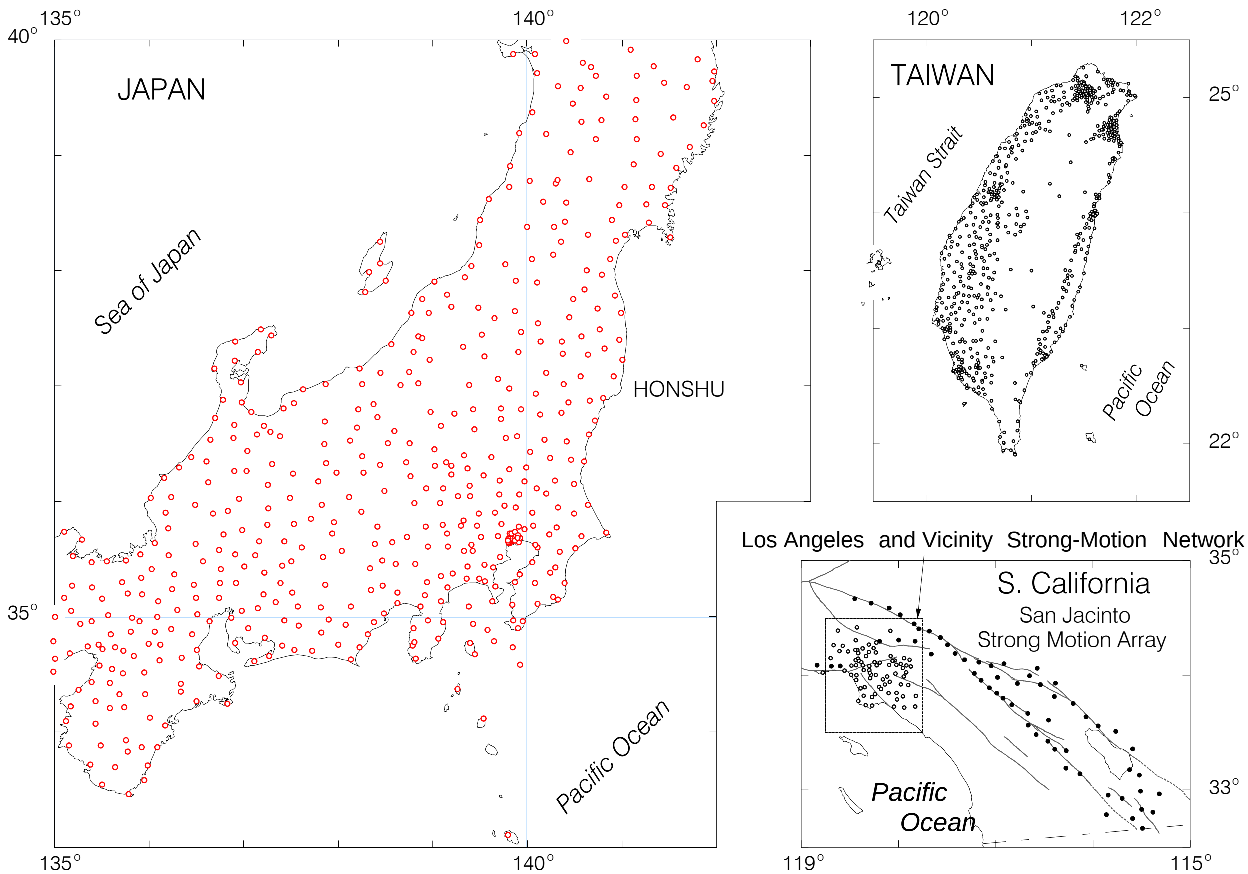

Fig. 19 Comparison of relative station densities of free-field strong-motion stations in Kyoshin-Net, (Fig. 13), CWB-TSMIP (Fig. 12), San Jacino (Fig. 8) and Los Angeles and vicinity (Fig. 9) strong-motion networks.

in early 1930s was between US $4,000 and $8,000, depending upon the quantity and the components. By 1970, the cost of one accelerograph went down to $1,600[9] (MO-2 and SMA-1).

Between 1970 and 1980, two changes occurred. First, the concept of one self-contained tri-axial accelerograph was broadened, and a centrally located multi-channel recorder was introduced,

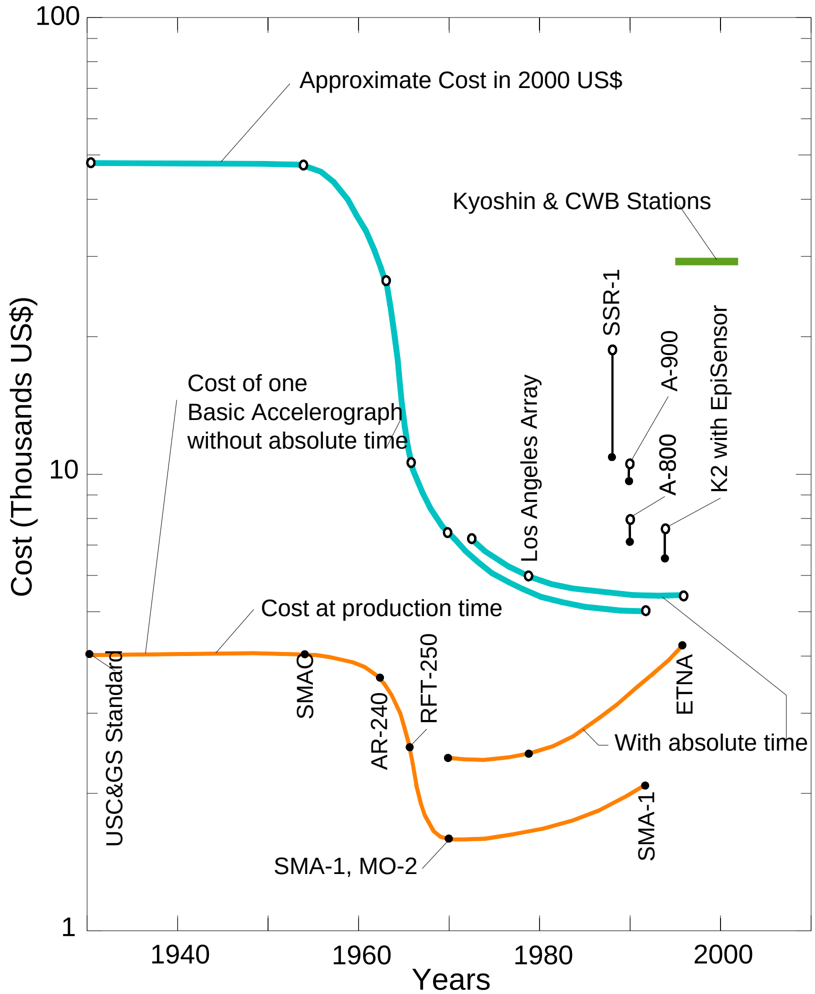

Fig. 20 Trends in the cost (in thousands of US $) of basic tri-axial accelerographs without, and with, absolute time-recording capabilities, and without any (or not using) remote-access capability of the Internet, telemetry, or telephone line. Also shown are examples of the basic cost of digital accelerographs (A-800; A-900; k2) that have absolute time and that are used in the networks with real- or near-real-time-data transmission to a central station. For comparison, approximate costs of one typical Kyoshin (Fig. 13) and CWB (Fig. 12) station are also shown. The top set of curves shows approximately the cost in 2000 US $.

being wired to a set of uni-axial or tri-axial transducers distributed in accordance with the specific plan for measurements, which depended upon the nature of the structure and its site. For example, in buildings, at first, groups of 13 channels (accelerometers) were tied to one or several centrally located galvanometric recoders.[125,126] Later, one or several multi-channel, centrally located digital recorders were used, with broad-band digitizers and computers to accommodate

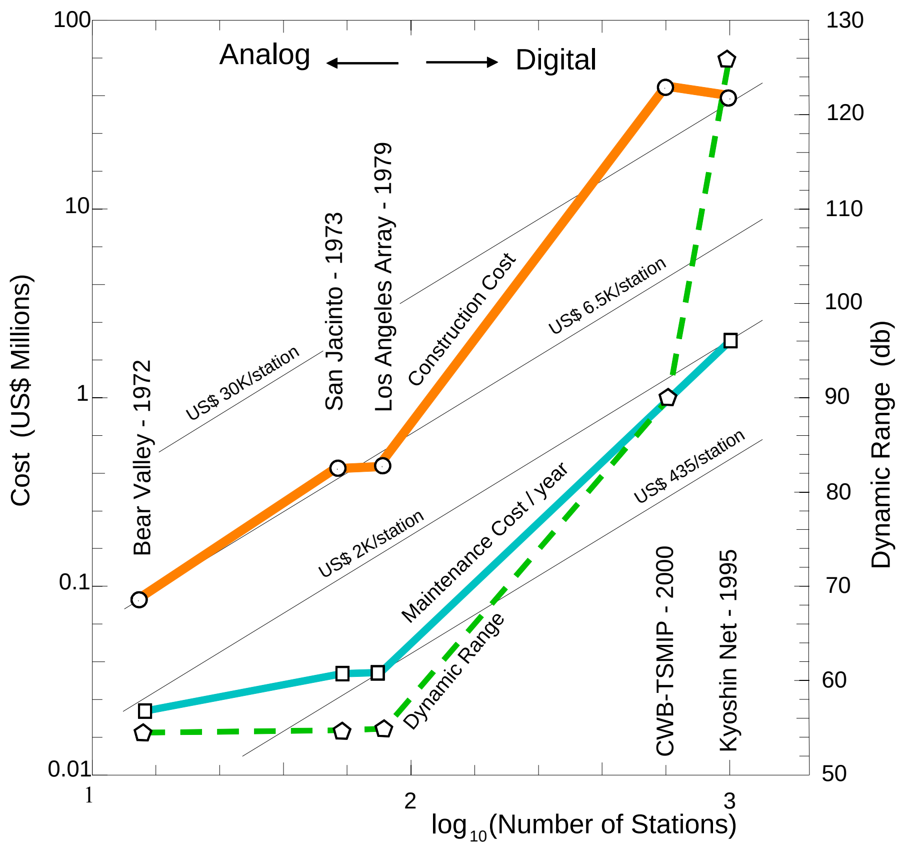

Fig. 21 Example of construction and of maintenance costs for three analog networks (Bear Valley, San Jacinto and Los Angeles, using the SMA-1 accelerograph with absolute-time code generator), and two digital networks (CWB and Kyoshin networks using A-800, A-900, K2, and K2-like accelerographs). Typical dynamic range capability of these networks is also shown with a dashed line.

real or near-real-time data transmission. Second, analog recording on film was gradually replaced by digital recording, first writing onto digital magnetic tape and more recently into solid-state memory. Simultaneously, the dynamic range of analog-to-digital converters started to increase, from about 55 dB (9 bits) prior to about 1975 to 135 dB with 24- and 26-bit systems at present.

The basic 18-bit digital acceleerograph, ETNA (Kinematrics), is not more expensive than what an SMA-1 might cost today. A basic K2 recorder (Kinematics), with tri-axial EpiSensor accelerometers, and tri-axial A-900 accelerograph (Teledyne), with dynamic range of 90 db, costs between US $6,500, and US $10,000, depending upon the configuration.

At present the feasibility of different solutions for real-time data transmission (devoted telephone lines, radio, internet), coupled with the insatiable quest for ever-larger dynamic range, have driven the cost of a typical tri-axial strong-motion stations to US $30,000 and beyond, or seven to eight times the cost of a basic tri-axial accelerometer. Future experience will show whether seven or eight times more dense networks would have been better for helping to bring about faster quantum jumps in our ability to design better earthquake-resistant structures.

There are different costs associated with the operation of strong-motion networks: (1) station preparation and installation, (2) maintenance, and (3) operation. Station preparation and installation includes the costs for instruments and for the telemetry; expenses for site selection, site preparation, and instrument preparation, testing and calibration; and the costs for equipment procurement and management. For both the San Jacinto array (in 1973) and the Los Angeles Vicinity Array (in 1979) the cost of one SMA-1 with a TCG-1 time recorder was less than $3000. With site selection, preparation, installation, calibration of each accelerograph[127,128] (natural frequencies, damping, sensitivity, and tilt tests) and TCG-1, the cost of construction of one station was about US $6,500. Deployment of one station in the CWB and Kyoshin networks was about US $30,000 (Fig. 21). Maintenance costs depend upon the accelerograph system, station environment, and spacing. For the Bear Valley, San Jacinto, and Los Angeles arrays, the maintenance and repair costs for instruments have been negligible over a long period of time (20 years). However, SMA-1 requires periodic replacement of batteries and film, at a cost of about $50 per station per year. For networks that use telemetry, the maintenance cost can be as much as 30% of the deployment cost per year. Maintenance cost also depends upon the size and geographic location of the array, which influences the travel time required to visit each station.

For the Los Angeles Array, the maintenance cost of $435/station/year is low due to the proximity of the stations and the fact that the array is maintained by staff who live locally. The maintenance cost of the Kyoshin net is about US $2,000/station/year. Operation cost for networks with analog recorders (without telemetry) is negligible. However, when data is recorded, the films have to be digitized and the data must be processed and placed onto a web for distribution. Spread over 20 years, this cost so far has been about $250/station/year for the Los Angeles strong-motion array. Operation of the Kyoshin net involves three full-time persons and one computer engineer.

Another important factor that influences the cost of operating strong-motion arrays is the useful life of the equipment. Analog accelergraphs, like SMA-1, can work for tens of years, requiring minimal repairs. Modern digital accelerographs use state-of-the-art computer components, which have only 5 to 10 years of useful life. While the useful life of transducers can be very long, analog to digital converters, digital recorders, and the computers used to process, store, and transmit the data will require periodic upgrading and replacement, and this will further add significantly to the operating costs. The great advantages of digital accelerographs are that (1) there is no need to digitize the data and (2) they can have excellent dynamic range (Figs. 5, 21). The disadvantage is that in the way digital instruments are used at present, with emphasis on real- or near-real-time data transmission to central stations, the typical station cost is almost one order of magnitude higher compared with the cost of one basic tri-axial analog or digital accelerograph. In the end, this significantly reduces the spatial density of stations and thus reduces our ability to study many important aspects of strong-motion waves.

4. RECORDING STRONG-MOTION IN BUILDINGS

This section reviews the recording of the earthquake responses of buildings and the use of these data for identification of soil-structure systems and for damage detection. It also discusses the variability of building periods, determined from strong-motion data, and the significance of this variability for the building codes and for structural health monitoring. At the end, it addresses the measurement of permanent displacements in structures and future challenges in recording and interpreting strong-motion in buildings.

4.1 Instrumentation

For many years, typical building instrumentation consisted of two (basement and roof) or three (basement, roof, and an intermediate level; Fig. 22a) self-contained, tri-axial accelerographs

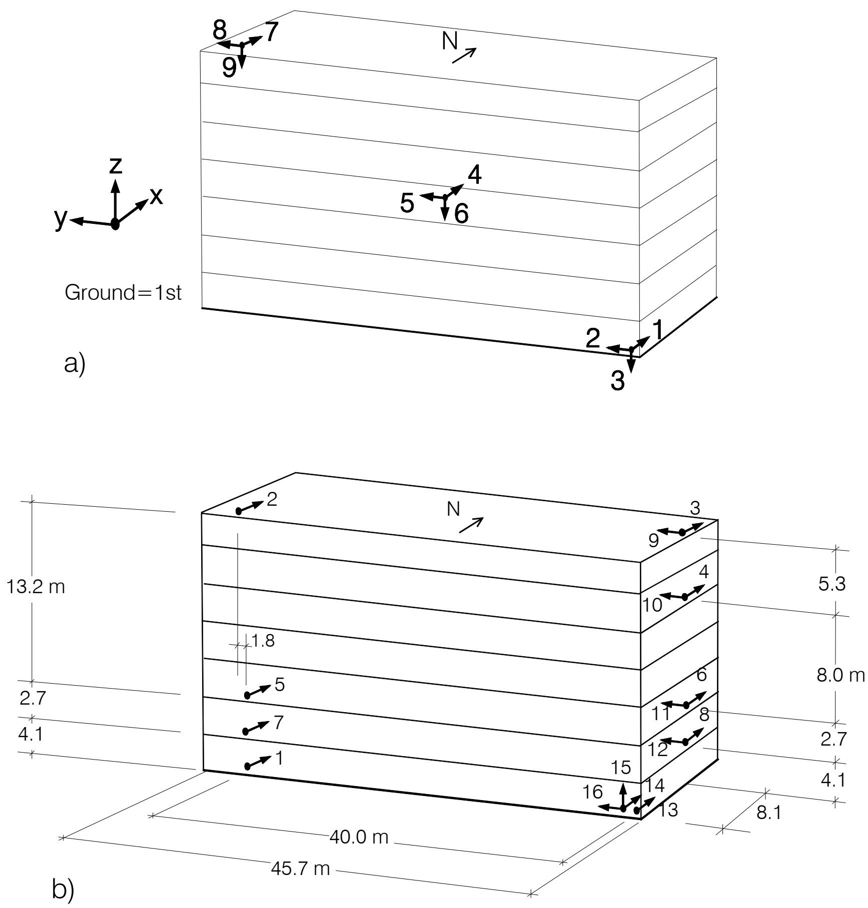

Fig. 22 Location of strong-motion recorders in the Van Nuys seven-storey hotel (VN7SH) before (part a) and after (part b) 1975.

interconnected for simultaneous triggering.[59] *The early studies of recorded motions noted that such instrumentation cannot provide information on the rocking of building foundations, information that is essential for identification of the degree to which soil-structure interaction contributes to the total response.*[129] Beginning in the late 1970s, new instrumentation was introduced with a central recording system and individual, one-component transducers (usually force-balance accelerometers; Fig. 22b). This instrumentation provided greater flexibility to adapt the recording systems to the needs of different structures, but *budget limitations* and the *lack of understanding of how different structures would deform during earthquake response* often resulted in *recording incomplete information.*[10, 130-132] The outcome has been that the *recorded data are used rarely in advanced engineering research*, and usually only to provide general reference for the analyses.

4.2 Damage Detection from Recorded Structural Response

One of the reasons for testing full-scale structures before, during and after earthquakes has been to detect damage caused by severe earthquake shaking.[123,124,133-135] In an ideal setting, the measurements should identify the location, evolution, and extent of the damage. For example,

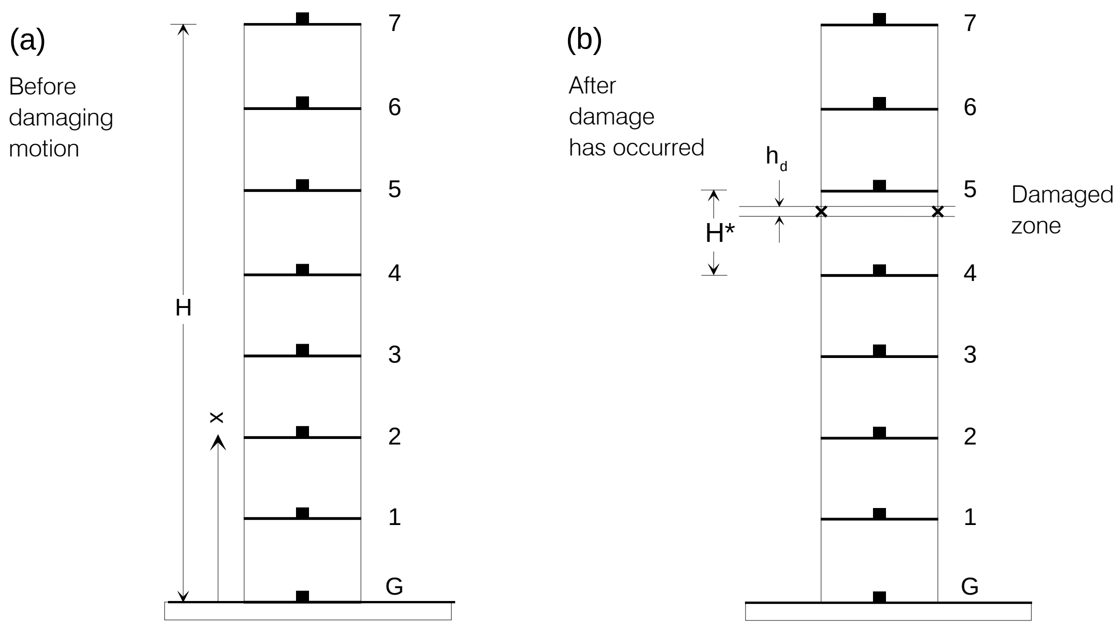

Fig. 23 A multi-degree-of-freedom system (a) before and (b) after localized damage has occurred (e.g., in the columns below the 5th floor). The solid squares indicate locations of the strong-motion instruments.

the recorded data would show the time history of the reduction of stiffness in the damaged member(s) and would identify the damaged member(s). Minor damage that weakens some structural members but does not alter the form of their participation in the overall stiffness matrix is expected to modify only those terms of the system stiffness matrix that correspond to those members. This will result in changes to the corresponding mode shapes[135] and natural periods of vibration.[136] Hence, a partially damaged member would reduce the overall stiffness of the system and would cause the natural periods of vibration to lengthen. A simple approach to structural health monitoring has been to measure these changes in the natural periods (usually the first period, T_1) before and after strong shaking.[129] However, there are at least two problems with this approach. The first is that such period changes are usually small and therefore are difficult to measure accurately.[137] The second problem is that the apparent system period, T, which is the quantity usually measured, depends also upon the properties of the foundation soil. That is,

$$T^2 = T_1^2 + T_r^2 + T_h^2 \quad (1)$$

where T_1 is the first fixed-base building period, T_r is the period of the building rocking as a rigid body on flexible soil, and T_h is the period of the building translating horizontally as a rigid body on flexible soil. The apparent system period, T, can and often does change appreciably during strong shaking, by factors which can approach two.[123,124,138] These changes are caused mainly by nonlinear response of the foundation soils, and they appear to be self-healing, probably due to dynamic settlement and compaction of soil during aftershocks and small earthquakes. To detect changes in T_1 only, special-purpose instrumentation must be installed in structures. With the currently available instrumentation in various buildings in California, one can evaluate changes in T, but separate contributions from T_r, T_h, and T_1 cannot be accurately detected.[129,139]

For periods shorter than T_1 (this corresponds to short wavelengths and to higher modes of building vibration), the soil-structure interaction effects become complex and must be analyzed by wave-propagation methods.[140] In principle, this higher complexity may offer improved resolution for the purposes of identification of the soil-structure parameters, and it depends upon our ability to model the system realistically,[10] but it calls for detailed, full-scale tests and dense strong-motion instrumentation arrays in buildings. Therefore, most studies consider measured data only in the vicinity of T.

To illustrate the order of magnitude of the changes in T_1 caused by damage, consider the model shown in Fig. 23. Assume that this model deforms in shear only, and let the period of the first mode of vibration be equal to T_1. Because the mode shapes represent the interference patterns of waves propagating up and down the structure,[141-143] T_1 is proportional to the travel time H/β. Before any damage has occurred,

$$T_1 = 4H/\beta, \tag{2}$$

where β is the shear-wave velocity in this structure and H is the height of the building. After strong shaking, some columns may have been damaged at a particular floor. Let h_d be the "length" of this damaged zone, and β_d be the reduced velocity of shear waves within this damaged zone. Then, the period of the first mode is proportional to

$$T_d \sim (H - h_d)/\beta + h_d/\beta_d\ , \tag{3}$$

and the percentage increase in T_d, relative to T_1 will be

$$p = \frac{100 h_d}{H}\left(\frac{\beta}{\beta_d} - 1\right). \tag{4}$$

For example, for H = 20 m, h_d = 0.5 m, β = 100 m/s and β_d = 50 m/s, p = 2.5%.

Whether simple measurements of wave velocity in structures during strong shaking can be carried out, and whether the location of the observed change (reduction in apparent wave velocity) will coincide with the areas of observed damage, was explored by analyzing strong-motion recordings in a 7-storey, reinforced concrete hotel building in Van Nuys, California (Fig. 22) that was severely damaged by the 1994 Northridge earthquake.[122] It was shown, that this task appears to be feasible, but accurate digitization of accelerograms recorded in buildings is essential,[134] before this type of analysis can be developed and further refined.[131-135]

Next, assume that recordings of strong-motion are available at two adjacent floors (Figs. 22 and 23) and that it is possible to measure the velocity of shear waves propagating in the structure.[131-134] Before damage has occurred, the travel time between two adjacent floors, i and j, would be

$$t_{ij} = H^*/\beta, \tag{5}$$

and after damage has occurred it would be

$$t_{i,j}^{d} = (H^* - h_d)/\beta + h_d/\beta_d, \tag{6}$$

where $H^* = H/N$ is the storey height and N is the number of stories (in this example, $N = 7$). The percentage change from t_{ij} to $t_{i,j}^{d}$ is then

$$p = \frac{100 h_d}{H^*}\left(\frac{\beta}{\beta_d} - 1\right). \tag{7}$$

For $h_d = 0.5$ m, $\beta_d = 0.5\beta$, and $H^* = 20/7$ m, $p = 17.5\%$. *This is N times larger than the percentage change in T_1* (because the observation "length" has been reduced N times).

For typical values $H^* = 3$ m and $\beta = 100$ m/s, $t_{ij} \sim 0.03$ s. The old data processing of strong-motion acceleration provided equally spaced data at 50 points/s. Since the early l990s, most data are processed with time step $\Delta t = 0.01$ s or 100 points/s.[55,144,145] Clearly, to detect time delays on the order of 0.03 s the accuracy of origin time and the accuracy of the time coordinates in digitized and processed data must be much better than 0.03 s.[131,132,134]

There is one obvious limitation of the above approach. It has to do with its ability to resolve "small" and concentrated zones of damage. It can offer only an order of magnitude (~ N) improvement over measurements of changes in natural frequencies. Of course, it is possible in principle to saturate buildings with transducers, densely distributed, on all structural members, but this is obviously not a practical alternative. The best we may expect, at present, is to have one instrument recording translation per principal direction per floor. In the near future, we may see two additional instruments per floor, each recording three components of rotation (two components of rocking about transverse and longitudinal axes and one component recording torsion). This will correspond to approximately three times better spatial resolution than in the above example.

4.3 Limitations and Suggestions for Improvement

At present, the state of the art in modeling structural responses during strong earthquake shaking is limited by the simplicity and non-uniqueness in specifying the structural models.[10] The lack of knowledge and the absence of constraints on how to better define these models comes mainly from the lack of detailed measurement of response in different structures during strong earthquake shaking. Thus, *until a quantum jump is made in the quality, detail, and completeness of full-scale recording of earthquake response, little change will be possible in the modeling techniques*. Conceptually and practically, earthquake-resistant design is governed by the procedures and sophistication of the dynamic response analyses that are feasible within the framework of the response-spectrum technique, which is essentially a discrete vibrational formulation of the problem. This formulation usually ends up being simplified further to some equivalent single-degree-of-freedom system deformed by an equivalent pseudo static analysis, assuming peak deflections (strains), which then determine the design forces. Over the years, the attempts to extend the applicability of this approach to nonlinear levels of response have resulted in *so many and such complex and overlapping "correction" factors that the further refinement of the procedures has reached the point of diminishing return*. The only way out is to start from the beginning and use a *wave-propagation approach* in place of the vibrational approach. However, again, this requires verification through observation of response using *far more dense networks of recording stations than what are available today* (e.g., Fib. 22b). This does not mean that nothing new can be learned from the currently available strong-motion data. To the contrary, a large amount of invaluable new information can be extracted from the recorded but never digitized data, and the methods currently in use can be further refined. At the same time, to prepare a sound experimental basis for future developments, far more detailed observational networks in structures must be deployed.

4.4 Variability of the Building Periods

The analyses of building response to earthquake shaking[123,124] show that the time- and amplitude-dependent changes in the apparent system frequencies are significant. For example, during twelve earthquake excitations of a seven-storey reinforced-concrete building between 1971 and 1994, the peak ground velocities, v_{max}, were in the range 0.94 to 50.93 cm/s. For average shear-wave velocity in the top 30 m of soil $\bar{v}_{S,30}$ = 300 m/s, the surface strain factors in the free-field[112,146] were in the range $10^{-4.7}$ to $10^{-2.8}$. During the Northridge earthquake excitation, the largest vertical shear strain associated with rocking of a building was on the order of 10^{-2}. Within the above strain range, the apparent frequencies of the soil-structure system, f_p, varied from 0.4 to 1.5 Hz (a factor of 3.8). The corresponding range of rocking accelerations was 10^{-4} to 2×10^{-1} rad/s^2, while the range of rocking angles was 10^{-6} to 2×10^{-2} rad.

From the nature of the changes in f_p (= 1/*T*) versus the excitation amplitudes, it appears that these changes were associated with the nonlinear response of the soil surrounding the foundation, including both material and geometric nonlinearities. Future research will have to show how much the observed range of changes is due to the fact that the building is supported by friction piles. There is no doubt that f_p changes during strong-motion for buildings with other types of foundations.[138] *What future research must determine is how broad these variations are for different types of structures and foundations and how common it is that the effective soil stiffness essentially regenerates itself after a sequence of intermediate and small earthquakes.* To carry out all of this research, it will be necessary to deploy *more dense instrumentation* (in the structures and in the surrounding soil).

4.4.1 Implications for Building Codes

Most code provisions approach earthquake-resistant design by evaluating the base-shear factor *C(T)* in terms of the “building period” *T*. Older analyses of *T* erroneously assumed that the effects of soil structure interaction were of "second order," [147] and some more recent studies either do not consider it explicitly[148-150] or approximate *T* by fitting the functional form of analytical representations of inertial interaction to the observed data on *T*.[150] All of these studies encounter large scatter in the data about the trend predicted by the assumed formulae for *T*, but, with few exceptions, most studies ignore the dependence of *T* on the nonlinear response of the soil.

Using linear identification techniques, it is common to estimate *T* for a linear soil-structure system (with or without an explicit attempt to identify T_r, T_h, and T_1). This means that for most studies that use actual earthquake data,[148] the estimates of f_p (that is 1/*T*) depend upon the average amplitude of the response in the data set included in the analyses. In addition, because in most cases there are only one or two analyzed earthquake excitations per building, these estimates are often used regardless of the level of excitation. There are other related simplifications in the code provisions, that should be reevaluated in light of the fact that f_p experiences the described fluctuations. An obvious (and in part compensating) effect is associated with the relationship between the dependence of the shape of *C(T)* on magnitude (usually ignored at present) and the dependence of *T* on the strong-motion amplitudes.[149,150] To identify the source and spatial extent of the material undergoing nonlinear deformation (soil, structure, or both) and contributing to the observed changes in f_p, *denser arrays of recording accelrographs will have to be installed*.

4.4.2 Implications for Structural Health Monitoring

Most algorithms for structural health monitoring and for control of structural response depend upon prior or real-time identification of the structural "system" in terms of a set of model parameters.[10] Only when and if the changes in *T* can be incorporated into advanced nonlinear models in such a way that only a manageable number of identified parameters can describe all of the relevant changes (including the ability of the soil to settle and densify during strong shaking, thereby restoring the original system stiffness) will the methods of structural health monitoring and response control be able to function. An interesting and challenging situation will occur when the system responds with a frequency higher than expected (on the basis of previous observations). To function, both structural health monitoring and control algorithms must be based on realistic models of structures and must be able to adapt in ways that can be modeled by other than "simple", "equivalent" models with a reduced number of degrees of freedom. The soil-structure interaction must be modeled realistically and must be included in the differential equations of the system response.

During the period from 1987 to 1994 (preceding the Northridge earthquake), the apparent frequencies of the seven-storey reinforced-concrete structure moved within the range from about 0.7 to about 1.8 Hz.[123,124] During this time, the building displayed no visible signs of distress or damage. During the Northridge earthquake, the longitudinal apparent frequencies were between about 0.43 and 0.91 Hz (a factor of 2.1), while the transverse frequencies ranged from about 0.47 to 0.92 Hz (a factor of 2.0). Thus, to be useful in real-life applications, structural health monitoring algorithms should be based not only on monitoring the changes in the system frequency but must also consider the proximity of the observed frequencies to those corresponding to levels of response leading to structural damage.[123,124] This will require (1) modeling of soil-structure systems where both the soil and the structure can enter the nonlinear range of response and (2) development of advanced identification algorithms to detect concurrently the levels of nonlinear response in the soil and in the structure. *To determine the spatial concentration and distribution of the nonlinear response, dense arrays of recording instruments will be required*.

4.5 Measurement of Permanent Displacement

The amplitude resolution of modern digital accelerographs recording translational components of strong-motion is currently in excess of 24 bits (about 135 dB). For earthquake engineering applications, this high resolution is not necessary unless rotational components of ground motion are recorded simultaneously, and it results in expensive instrumentation. For calculation of permanent displacements of damaged structures and of permanent displacement of the ground in the vicinity of shallow and surface faults, it is essential to record all six degrees of freedom (three translations and three rotations).[151] Otherwise, *the rotational components of strong ground motion begin to appear above the recording noise, starting with resolutions of 11 to 12 bits (~ 70* *dB).*[152] *Recording only three translations with resolution higher than 12 bits does not improve the recording accuracy, because the contributions of the rotations become part of the translational record and cannot be eliminated. Thus, to compute permanent deformation in buildings (following damage) and in soil, it will be necessary to develop commercially available strong-motion instruments that measure all six components of motion.*

4.6 Future Challenges

Studies of the spatial distribution of damaged buildings and breaks in the water distribution pipes following the 1994 Northridge earthquake showed that *the damage to one-storey, residential, wood-frame buildings was significantly reduced in the areas where the soil experienced nonlinear response.*[110,111] This has been interpreted to mean that nonlinear soil absorbs part of the incident wave energy, thus reducing the power and the total energy available to damage structures.[112,116] The presence of piles beneath a building foundation increases the scattering of the incident-wave energy from the volume of soil and piles, which can be stiffer than the surrounding soil. Then the forced vibration of the entire pile-foundation system creates a volume of anisotropic "soil" with the capability to absorb a considerable amount of incident-wave energy, and also with a natural ability to recover some or all of its pre-earthquake stiffness, through shaking by aftershocks and small earthquakes. It is beyond the scope of this chapter to analyze this energy-absorption mechanism. It should be clear, however, that it represents a powerful, convenient, and inexpensive "base isolation and energy absorbing system", that in many ways is superior to the conventional base-isolation methods (e.g., it does not introduce discontinuities into the soil-structure system, it can be designed as an extension of common foundation systems on piles, and it scatters and absorbs the incident seismic energy *before* this energy enters the structure). *The challenges for future work are to quantify these phenomena, by using dense strong-motion measuring networks, to verify the repeated occurrence and predictability of the phenomena, and to implement this approach into the future design of similar pile-supported structures.*

5. DATA PROCESSING

5.1 Early Digitization, Data Processing, and Computation of Response

5.1.1 Computation of velocities and displacements

Systematic studies of the digitization of accelerograms and of the computation of ground velocity and displacements were initiated at USC&GS, the National Bureau of Standards, and the Massachusetts Institute of Technology, soon after the first recording of strong-motion in 1933.

For numerical integration, recorded accelerograms first had to be digitized. Enlargements of original paper records were made by a lantern projector (a "Balopticon") capable of projecting opaque objects with magnification of about seven times. Enlargements were made on high-grade cross-section paper shellacked to an aluminum plate.[153,154] For comparison with numerical integration, which was carried out at USC&GS, and to study the accuracy of the overall procedures, shaking table tests were conducted at the Massachusetts Institute of Technology, in which true translational motion, applied to the accelerometers, was accurately recorded simultaneously with the accelerometer response.[20,155] To excite accelerometers with small accelerations at long periods, a microtilt mechanism was used.[18] The recorded accelerograms were then integrated by the M.I.T. Differential Analyzer[155], by a mechanical analyzer at USC&GS,[156] and by numerical integration.[154]

A torsional pendulum analyzer was made at USC&GS in 1936, to determine displacement from acceleration mechnically[156,157]. It was based on the principle that a torsional pendulum, with a long (10s) natural period, can be used to determine the displacement of ground recorded by an accelerometer[154,158,159].

Neumann's paper,[154] presented during a symposium on "Determination of True Ground Motion by Integration of Strong-Motion Records," reviewed the ideas, concepts, and methods, which were explored and tested in the 1930s, as the subject of strong-motion data processing started to evolve.

5.1.2 Computation of response spectra

The concept and the ideas leading to the response spectrum method were formulated in 1932 by Maurice Biot,[160,161] and fully developed by him during the following 10 years.[162] Response Spectra describe the maxima of the relative response of simple oscillators to a given strong-motion acceleration and can be computed, for example using Dahamel's integral. Prior to the age of digital computers, this computation presented a formidable task.[163]

The first practical method for computation of response spectra, developed during the late 1930s was based on the torsional pendulum analog,[159] and it required about eight hours to construct one spectrum curve consisting of 30 points.[162] Prorated, this is equivalent to 7,200 minutes, or 120 hours, for computation of one modern response spectrum, for one component of acceleration, at 91 periods, for five damping values (Fig. 24). During the 1950s, analog computers were developed and were used for computation of response spectra, but the accuracy and repeatability of computations remained poor.[163] The modern era of computing response spectra began in the mid- 1960s with introduction of the IBM 7094 digital computers.

5.2 Modern Digitization

5.2.1 Mechanical-electrical digitization

In 1968, D.E. Hudson, at Caltech, initiated the first systematic accelerogram digitization and processing project.[51] He purchased a mechanical-electrical digitization table (Benson Lehner 099D, with maximum resolution of 800 dpi) with a mechanically controlled cursor with cross-hairs. By placing the cross-hairs over the center the of the acceleration trace and actuating a button by foot, the operator would activate the analog-to-digital converter, producing digital equivalents of x and y coordinates on the table. These coordinates were next sent to the IBM card-punching machine. In several hours, even the most complicated accelerogram could be digitized.[54] It was with this mechanical-electrical digitizer that the author digitized many classical strong-motion accelerograms (e.g. the Long Beach Public Utilities Building record from 1933,[22] the El Centro accelerogram from 1940,[23] and the Pacoima Dam accelerogram from 1971[25]).

5.2.2. Semi-automatic digitization

5.2.2.1.Rotating-drum scanner at USC

By the time it was completed in 1975, Hudson's strong-motion data digitization and Processing Project produced 186 free-field records and two or three tri-axial records per building for approximately 55 buildings. During this project, it took, on the average, 4 days to complete the digitization process for one accelerogram: one day for digitization; one day to copy computer cards onto magnetic tapes; one day to plot digitized data onto a transparent paper, place it over the original record; check the accuracy of digitization, and correct any errors; and one day to write the final files onto magnetic tapes and punched cards. This project demonstrated the need for a faster and more efficient digitization method.

In 1978, the first semi-automatic, computer-controlled digitization system was developed. It used the Optronics drum scanner, which was controlled by a Data General Nova 3 computer. Curve-following software was used to identify all simple segments of traces on film. Interactive software was then run by the operator, using a Tectonics Graphics terminal, to correct and to complete segments that automatic software could not decipher.[55] Another digitization system based on laser scanning and curve following was operated by IOM/Towill.[164] Other scanning systems were developed in Japan[165] and Italy.[166]

5.2.2.2. Flat-bed scanners

By the mid-1980s personal computers became powerful and fast enough to perform demanding calculations. Flat-bed scanners became commercially available at about the same time. By the mid-1990s, the capabilities of personal computers and flat-bed scanners exceeded the minimum requirements for semi-automatic digitization of analog accelerograms. The software developed to work with the Optronics drum scanner and with the Nova computer was then modified, creating the new LeAuto software package,[145] for use with personal computers and flat-bed scanners. This system can scan analog film or paper records with selectable resolution of 300, 600, or 1,200 dpi using 256 levels of grey scale. Very difficult (e.g., dark) segments of film can be digitized externally or separately, with any convenient magnification, and imported using

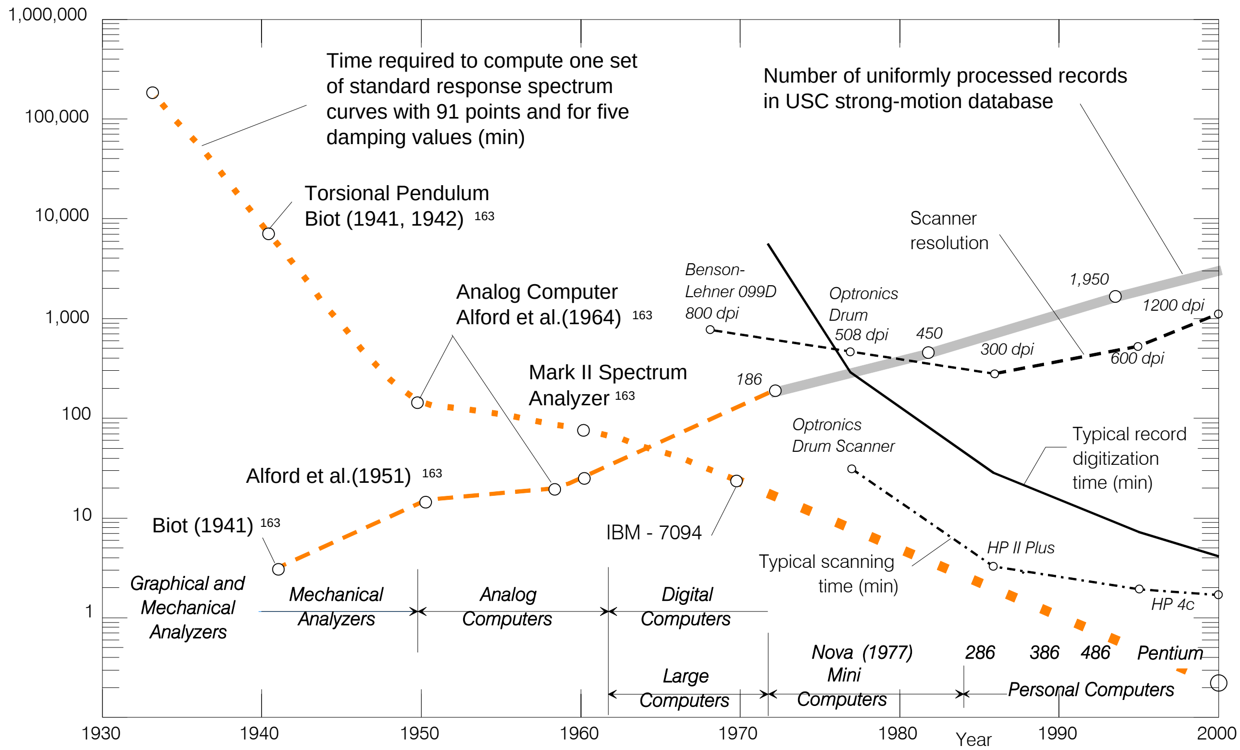

Fig 24 Trends in the capabilities of accelerogram digitization and data processing between 1930 and 2000: time required to compute one set of standard response spectrum curves (in minutes), and the cumulative number of accelerograms in strong-motion databases (light dashed line for the period prior to 1970), and in the uniformly processed strong-motion databases (wide gray line for the period after 1970).

specially prepared fiducial points. Advanced automatic selection of trace beginning was developed in 1993 to correct for the fact that for most analog records acceleration traces do not all have the same *x* (time) coordinate. This correction is essential if digitized longitudinal and transverse acceleration data are to be used in a rotated coordinate system. Without such a correction, acceleration in a rotated coordinate system contains unknown time shifts inherited from the original shifts in digitized data, and the end result may appear as incoherent motion even at closely placed stations. Accurate digitization of the starting point for each acceleration trace is important for coherence studies of strong-motion in free-field,[106] and for wave propagation studies in buildings.[134]

Figure 24 summarizes some of the above-described trends. It shows the typical scanning time (for the Optronics drum scanner and the HPII Plus and HP 4c flat-bed scanners) and the typical record digitization time. It can be seen that from about 4 days (5,760 minutes) per record in 1971 digitization time has been reduced to about 5 minutes. This is equivalent to a time reduction factor of more than 1,000 during a period of 30 years. Optical capabilities of the Optronics drum scanner are still better than those of most modern flat-bed scanners. For digitization of accelerograms, 50 × 50 micron pixels were used with Optronic drum scanner (this is equivalent to 508 dpi), even though the drum was capable of operating with 12 × 12 micron pixels (i.e., 2116 dpi). Modern scanners can exceed the optical resolution of 1,200 dpi, but experience shows that optimum pixel sizes for digitization of typical analog accelerograms, which give the best and the most stable results, are 600 dpi.[58]

Figure 24 also shows the required time (in minutes) to compute one set of response spectra for 91 periods and 5 damping values. At present, this time is measured in seconds. Finally, Fig. 24 shows the increase in the number of strong-motion accelerograms in USC's uniformly processed strong-motion data-base (wide grey line). Currently, this number exceeds 2000.

5.2.3 Digital Accelerometers

Digital accelerographs have a built-in analog-to-digital converter that converts the analog signals from the transducers into digital numbers, which are then stored in a solid-state memory. Thus, the digitization process is not required, although some conversion and pre-processing must be done because of the way the data are stored into the instrument memory.

5.3 Modern Data Processing

Modern principles for processing digitized strong-motion data were formulated during the late 1960s, soon after the appearance of digital computers and concurrent with the project of systematic digitization of strong-motion accelerograms. The basic elements of modern data processing were first summarized in 1973,[144] and they were later improved and expanded to accommodate new developments in computing and scanning hardware.[55,145]

5.3.1. Basic scaling and creation of raw data files

At this (the first) stage in data processing, named Volume I,[167] manually digitized data from

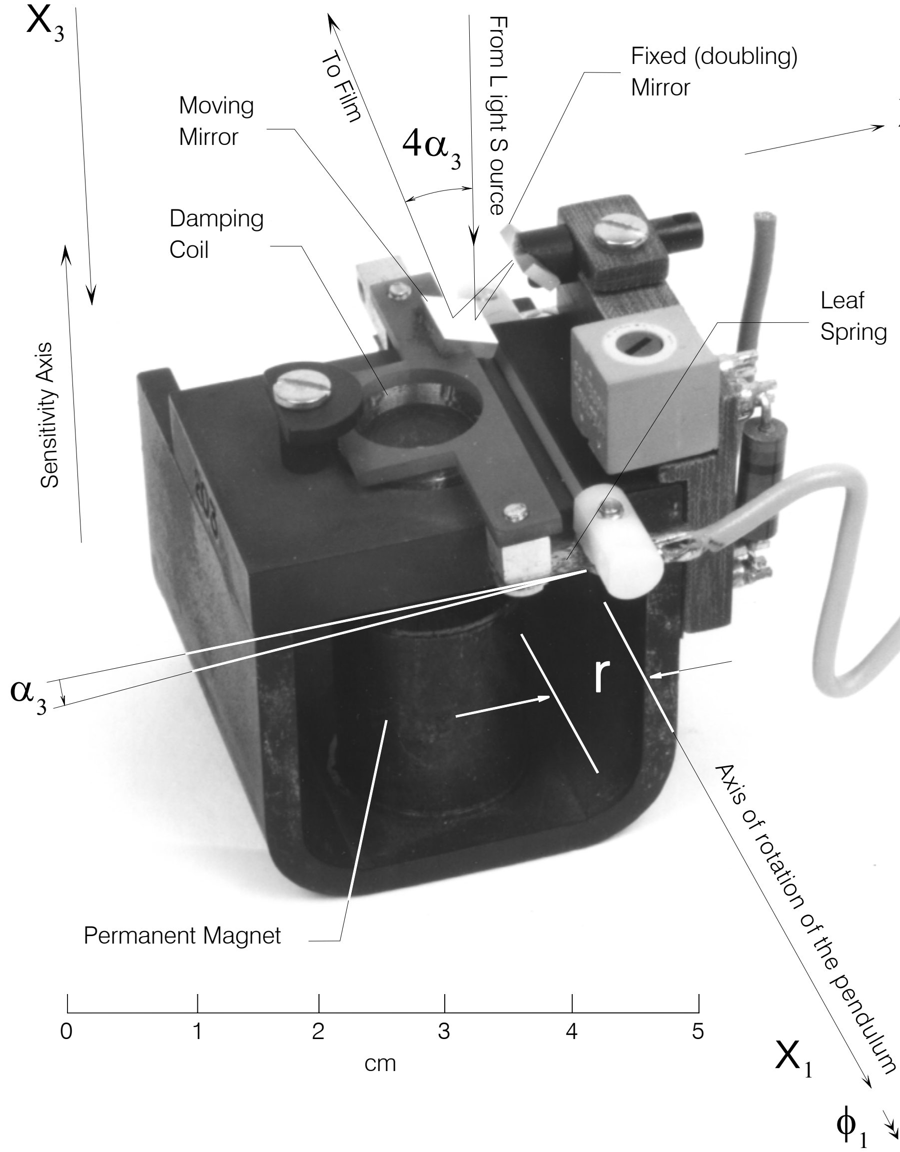

Fig. 25 An SMA-1 transducer removed from the box. Letter r indicates the arm of the pendulum, and α is the angle of deflection. A double reflection of the light beam from the mirror attached to the pendulum creates rotation of the light beam by 4α. The coordinate axes X_1, X_2, and X_3, and the angles of rotation α_3 and ϕ_1 are chosen to illustrate the configuration of a transducer sensitive to vertical motion.

mechanical-electrical digitizers, data from semi-automatic digitizers, or data from the memories of digital acceelrographs, are scaled and reformatted for subsequent processing. Manually digitized records had unequally spaced data, giving, on the average, 30 to 50 points per second. The *x* (time) coordinates of this data are first corrected for any variations in paper or film speed by interpolating actual-time coordinates from the smoothed digitization of timing marks, typically showing as two pulses per second, along the edges of film or paper records. For analog records that have fixed traces (produced by fixed mirrors), digitized acceleration data are measured relative to the concurrent amplitude of the nearest fixed trace and are then detrended using a straight-line fit by least squares. Finally, the y coordinates, in the units of the digitizing table are scaled to represent acceleration. Similar steps are used for Volume I processing of data from semi-automatic digitization and from digital accelerographs.

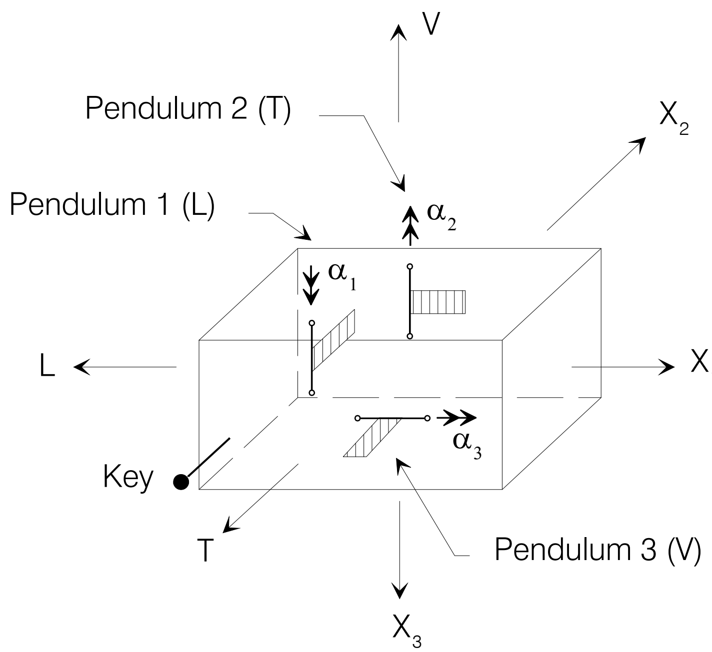

Fig. 26 Schematic representation of three transducers in an SMA-1 accelerograph. The coordinate axes X_1, X_2, and X_3 serve to describe the motion of the *L*, *T*, and *V* transducers, respectively, and are oriented in the opposite direction of the sensitivity axes to the transducers. Angles α_1, α_2, and α_3 describe the deflection of the transducer penduli.

5.3.2 Correction for instrument response

Many strong-motion transducers are (or are equivalent to) penduli that rotate due to acceleration of their supports. Their motion is recorded by deflecting a light beam projected onto paper or film,[2,3,29,51,168,169] by induction of voltage in a coil moving in a permanent magnetic field,[30] by recording the current in a coil proportional to the inertial force of the transducer mass, or by measuring relative displacement using variable capacitance.[170,171] Figure 25 shows an example of a viscously damped (by a moving coil in a magnetic field) pendulum transducer used in an SMA-1 strong-motion accelerograph.[127] The arm of the pendulum is designated by *r*. The sensitivity axis and the axis of rotation of the pendulum are also shown. The mutual placement and relative orientation of the

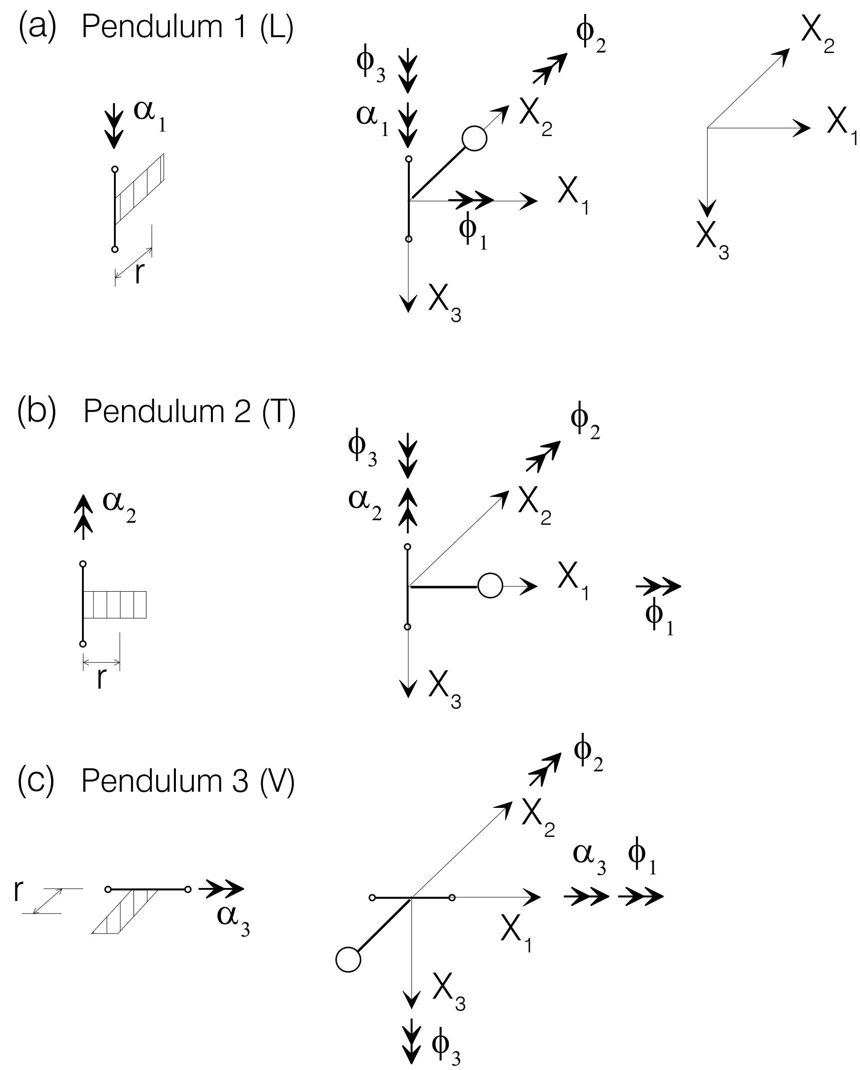

Fig. 27 Deflection angels of transducer penduli α_1, α_2, and α_3; rotation components of ground motion ϕ_1, ϕ_2, and ϕ_3 (shown by double arrows); and translational components of ground motion X_1, X_2, and X_3.

transducer penduli with respect to the longitudinal (L), transverse (T) and vertical (V) axes of an SMA-1 accelerograph are shown in Figs. 26 and 27, where X_1, X_2, and X_3 are, respectively, displacements positive in the directions opposite of the L, T, and V axes, and ϕ_i is a rotation about the X_i axis. For small deflections, $y_i = r_i\alpha_i$, where α_i is the angle of deflection of the i-th pendulum from its equilibrium position, the equations of motion of the penduli are[151]

$$L: \quad \ddot{y}_1 + 2\omega_1\varsigma_1\dot{y}_1 + \omega_1^2 y_1 = -\ddot{X}_1 + \phi_2 g - \ddot{\phi}_3 r_1 + \ddot{X}_2\alpha_1 \ , \tag{8a}$$

$$\mathrm{T}: \quad \ddot{y}_2 + 2\omega_2\varsigma_2\dot{y}_2 + \omega_2^2 y_2 = -\ddot{X}_2 - \phi_1 g + \ddot{\phi}_3 r_2 + \ddot{X}_1\alpha_2, \text{ and} \tag{8b}$$

$$\mathrm{V}: \quad \ddot{y}_3 + 2\omega_3\varsigma_3\dot{y}_3 + \omega_3^2 y_3 = -\ddot{X}_3 - \ddot{\phi}_1 r_3 - \ddot{X}_2\alpha_3, \tag{8c}$$

where ω_i and ζ_i are, respectively, the natural frequency and fraction of critical damping of the i-th transducer. The second and third terms on the right-hand side of equations (8a) and (8b) represent contributions from titling (ϕ_1 and ϕ_2) and angular acceleration ($\ddot{\phi}_3$) to the recorded responses y_1 and y_2. The tilting of the instrument does not contribute to the linearized equation for y_3 (8c), but the angular acceleration $\ddot{\phi}_1$ does. The last terms on the right-hand side in all three equations represent the contribution to the response from cross-axis sensitivity.[127,172]

In typical computation of translational velocities $(\dot{X}_i)$ and displacements (X_i) from recorded accelerograms, the contributions of all terms on the right-hand side of Eqn (1) (i.e., the forcing function terms) except $\ddot{X}_i$ are neglected. This is justified as long as the Fourier spectrum amplitudes of the neglected terms are smaller than those of the recording, digitization, and processing noise combined. Regrettably, as Graizer[173] pointed out, the completeness of representing Eqn (8) in literature varies. For example, Golitsyn[29] does not take into account the cross-axis sensitivity, while Aki and Richards[174] ignore the angular acceleration terms.

Fig. 28 illustrates the combined contribution of $\phi_i g$ and $\ddot{\phi}_i r_j$ to the response of a horizontal transducer, neglecting the contribution of cross-axis sensitivity and transducer misalignment.[128,175] It is seen that for small r (in this example equal to 8 mm) the $\phi_i g$ terms are the main terms contributing to the modification of the transducer response. Fig. 28 also shows typical spectra of ambient noise for a "noisy" and "very noisy" site. The upper hatched area represents spectra of typical digitization noise in analog records (digitized manually or

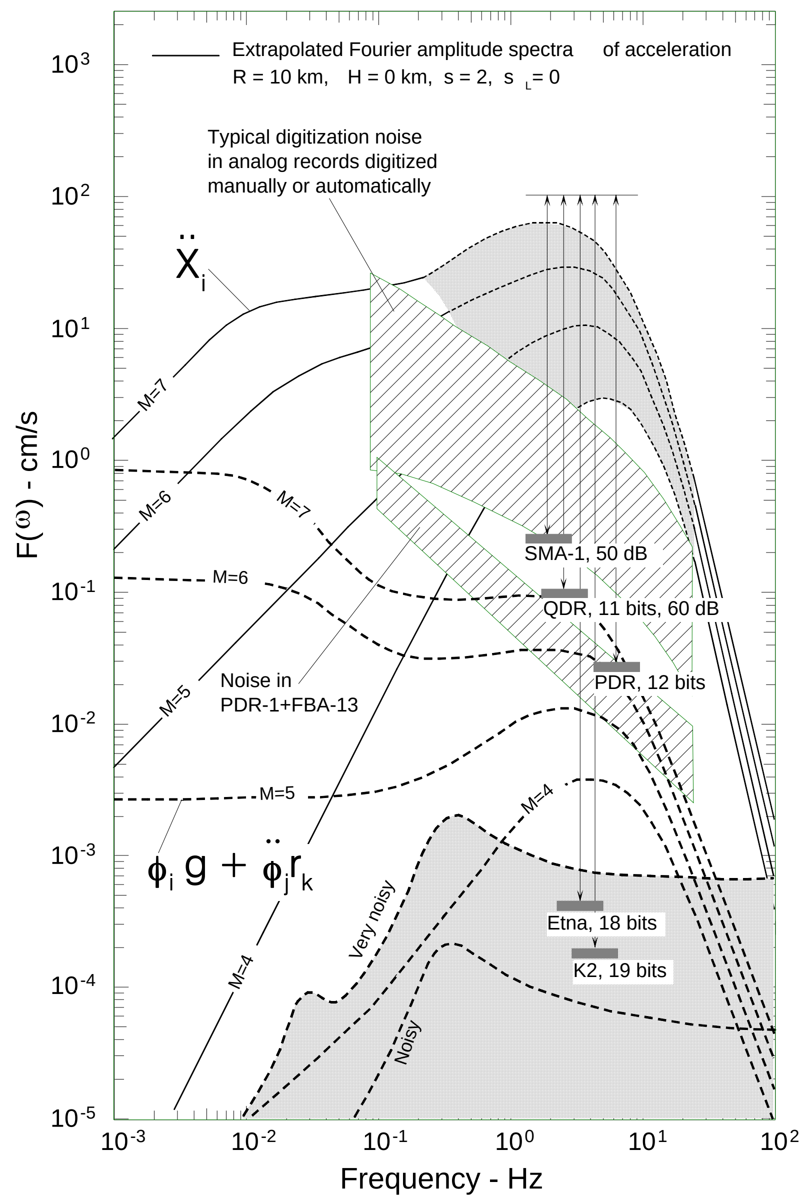

Fig. 28 Comparison of Fourier amplitude spectra of translation, $\ddot{X}_i$, with spectra of contributions from $\phi_i g + \ddot{\phi}_j r_k$, analog digitization noise, digital digitization noise (PDR), and microtremor and microseism noise.

automatically), and the lower one spectra of noise in PDR-1 with FBA transducers. The threshold recording levels for several strong-motion accelerographs and recorders (SMA-1, QDR, PDR, ETNA, and K2) are also shown. It can be seen that for the digital recorders with resolution higher than 11 to 12 bits the contribution of ground rocking cannot be ignored in computation of permanent displacements in the near field.

Fig. 28 shows that even for the most accurate digitization of analog records the digitization noise is larger than the largest contributions from the spectra of $\phi_i g$ in Eqn (8) (assuming linear-wave propagation for all strong-motion amplitudes). Therefore, for linear wave motion (in the far field) the contribution to "translational" records coming from the titling of accelerographs through angle ϕ_i can be neglected. For a 12-bit PDR-1 recorder, however, the effect of tilting can become comparable to and larger than the digitization noise and cannot be neglected. Finally, it should be clear from Fig. 28 that recording only translational accelerations with 18- and 19-bit recorders (e.g., ETNA or K2, both manufactured by Kinematics, Inc.) without recording rotation is costly and not necessary. This can allow seismological recording of smaller earthquakes and aftershocks, but it cannot contribute to accurate calculation of permanent displacements of the ground and of structures in the near field.[176,177]

For acceelrographs that record directly onto paper or film, what is recorded are deflections (rotations) of transducers y_i. For coupled transducer-galvanometer systems, what is recorded is the deflection (rotation) of galvanometers, and the extraction of ground motion requires analysis of six coupled differential equations. That is, each of the above equations (8a,b,c) must be expanded to include additional forcing terms caused by motion of the galvanometers, and three additional equations must be written to describe oscillations of the galvanometers.[30] When force-balance transducers are used, the above equations (8a,b,c) must be modified so that the frequency ω_i and damping ζ_i terms involve both mechanical and electrical terms.[170,171]

Corrections of digitized strong-motion data for instrument response then aim to extract the true ground motion from the recorded signals. For data recorded with analog accelerographs, having a dynamic range less than about 55 db (9 bits) the ϕ_i, $\ddot{\phi}_i$ and α_i terms on the right-hand side of Eqn. (8) can be neglected, and the recorded responses y_i can be used to compute $\dot{y}_i$ and $\ddot{y}_i$. For accurately calibrated values of ω_i and damping, ζ_i , $\ddot{X}_i$ can then be computed.[178] Numerical algorithms for correction of instrument response for force-balance accelerometers can be found in Novikova and Trifunac,[179] and for coupled transducer-galvanometer systems it can be found in Novikova and Trifunac.[30]

5.3.3 Baseline correction

Figure 29 shows the schematic shape of Fourier amplitude spectra of a digitized signal, which contains recording and processing noise. Short and long periods, T_L and T_R, where the spectrum

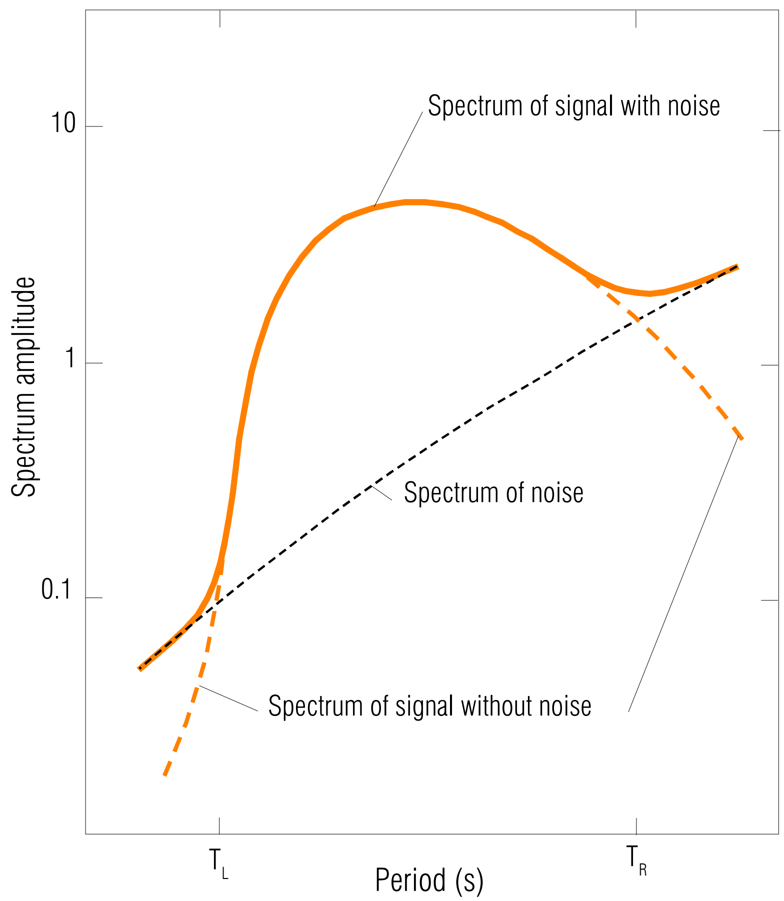

Fig. 29 Schematic representation of a spectrum of a digitized strong-motion accelerogram (solid wide line). It is a spectrum of true ground motion (i.e. without recording and processing noise; dashed line), combined with recording and processing noise. Modern data processing provides band-pass filtering of digital data between T_L and T_R.

of signal becomes smaller than the spectrum of digitization and processing , both depend upon earthquake magnitude epicentral distance and the recording site conditions.[56,57] For destructive strong-motion, in the near field when epicentral distance is small, T_L is usually less than 0.04 s.

For very large amplitudes of strong-motion (e.g., M > 7 and R < 10 km), T_R can exceed 20 s, but for moderate and small earthquakes it can be as small as 1 s.

Long-period recording and processing noise can be reduced significantly by measuring acceleration traces relative to the fixed-baseline traces during digitization — assuming, of course, that analog records have one or two fixed traces. The modern baseline correction of accelerograms then involves two steps: (1) careful selection of T_R, and (2) high-pass filtering of the accelerograms — that is, keeping only the frequency content in the data beyond $f_R = 1/T_R$ Hz.[180] Characteristic amplitudes and spectral shapes of the recording and digitization noise can be studied for different strong-motion instruments and for different digitization systems,[55-57,152],stored in a computer memory, and then $f_R = 1/T_R$ can be chosen by software automatically, in the pre-processing stage of baseline correction.[181]

5.3.4 Advanced data processing

For an ideal accelerometer, sensitivity vectors of three transducers would be (1) mutually perpendicular and (2) oriented exactly along the nominal sensitivity axes of the instrument box L, V and T (see Fig. 26). Departure from this ideal configuration is called mis-alignment. Mis-alignment manifests itself through additional forcing terms on the right-hand side of Eqn. (8). Typical misalignment angles are small, normally less than 1° to 2°, and only rarely reach 5°.[127,128]

Misalignment of transducers cannot be avoided, but actual misalignment angles can be measured by a series of tilt tests, and then, in the data processing for corrected accelerograms, the errors caused by misalignment can be eliminated. For the Los Angeles array of strong-motion accelerogrphs, for example, misalignment angles are documented for each SMA-1 accelerograph, and once a year, during routine field visits, the positions of all traces are recorded to detect any time dependent changes. During data processing, these angles are used to eliminate misalignment errors from corrected accelerograms.

Cross-axis sensitivity of typical transducers is represented by the right-most terms in Eqn. (8) for transducers that can be described by equivalent penduli. Errors introduced into recorded accelergrams by cross-axis sensitivity terms can be corrected exactly,[127,172] and these corrections can be performed simultaneously with corrections for misalignment errors.[128] Cross-axis sensitivity errors are pulse-like in time and occur during large peak accelerations, which impart large transducer deflections α_i. For example, a large pulse $\ddot{X}_2$ will contribute additional deflection α_3 during large accelerations $\ddot{X}_3$ (see Fig. 25).

Data processing — which begins with the scaled raw data of Volume I and then incorporates corrections for instrument response, determination of baseline, correction for misalignment, cross-axis sensitivity, and finally calculations of velocity and displacement time histories — is collectively termed Volume II processing. The corrected accelerograms, usually presented as equally spaced points in time (50 or 100 points per second) are also called Volume II data. Volume II data can be used for calculation of Fourier and response-spectrum amplitudes or for any other analysis of recorded strong-motion.

5.4. Data Post-Processing

Relative response spectra showing the maximum response of single-degree-of-freedom oscillators have became the standard starting point for almost all aspects of earthquake engineering design. Because it was a major computational effort to calculate Response spectra before the age of digital computers, it became a tradition to prepare various response spectrum curves as a part of routine processing of strong-motion accelerograms.[182] Today this tradition continues.

Following the first recordings of strong-motion (the Long Beach, 1953; Helena, 1935; Ferndale, 1937; and El Centro, 1940 earthquakes), a torsional pendulum spectrum analyzer (TPSA) was used to compute response spectra.[159] TPSA did not require digitization of the recorded accelerograms. A mechanical follower was used to convert the acceleration to rotation of the end of the torsional wire supporting the pendulum.

During the 1950s, analog computers were used for calculation of response spectra, but in spite of their many advantages over the TPSA the accuracy and reliability of calculations continued to be a major problem.[126,163] The first modern algorithms for calculation of response spectra were written in the 1960s, but with the IBM 7094 computer it still took about 20 minutes of computer time for one set of spectral curves[144]. This motivated research on how to develop fast algorithms to generate calculations of response.[183,184] With the speed of modern computers today, it may be best to use the exact algorithms based on the exact integration of Duhamel's integral for piecewise straight-line approximation of accelerograms between two consecutive digitized points.[163,185]

6. DATA STORAGE AND DISSEMINATION

6.1 Data Archiving

Storage of original paper or film records of strong-motion acceleration is not difficult. At present ,the number of paper records is not increasing. Many analog instruments recording on 70 mm film are sill in operation, and they occasionally produce a considerable number of records, but the space required for archiving such records is small and easy to organize. Storage of new digital data is not well defined at present, and there will be many changes before long-term solutions are adopted for archiving various formats of the original digital accelerograms.

6.2 Data Presentation and Access

The first reports on recorded strong-motion data were published in the form of journal papers and showed recorded accelerograms with significantly reduced scale, sufficient to show the general character of motion but too small to use for reproduction or digitization. An example of such a report, which also includes a description of a strong-motion accelerograph and shows all strong-motion accelerograms recorded during the March 10, 1933 earthquake in Long Beach, is presented in Chapter 2 of "Earthquake Investigation in California 1934 — 1935" published by the U.S. Department of Commerce.[3]

The first reports of recorded strong-motion accelerograms appeared in Japan in 1960. The Strong-Motion Earthquake Observation Committee,[26] at the Earthquake Research Institute of Tokyo University published, full-scale copies of SMAC and DC accelerograms. Basic data on each contributing earthquake and the location of the accelerographs were included. During the next 14 years (1960 to 1974), this committee published fourteen such reports, including a special report on the strong-motion data recorded during the Niigata earthquake of June 16, 1964. From 1970 to 1974, the Committee published odd-numbered reports (Nos. 9, 11, 13, 15, and 17). The National Center for Disaster Prevention (No. 15-1, Ginza 6-Chome, Chuo-ku, Tokyo 104) published five even-numbered reports (Nos. 10, 12, 14, 16, and 18). In 1974 and 1976, the Strong-motion Observation Council published reports No. 19 and 20 but presented photographically reduced images of the original records. Strong-motion accelerograms recorded at highways, bridges, tunnels, dams, and embankments were published in the reports of the Public Works Research Institute[186] (e.g., earthquake records for 1968, 1969, 1970, and 1971).

Between 1969 and 1975, Hudson, Trifunac, and Brady published 76 reports at Caltech's Earthquake Engineering Research Laboratory. Reports EERL 70-20 through EERL 73-30 presented uncorrected accelergrams in Volume I format.[167] Reports EERL 71-50 through EERL 75-53 presented corrected accelerograms with Volume II data.[182] Reports EERL 73-80 through EERL 75-83 presented response and Fourier spectra in the form of Volume III data,[188] and reports EERL 73-100 through EERL 75-101 presented the Fourier amplitude spectra as Volume IV data.[187] All of these reports have been distributed online by the Caltech Library System (http://caltecheerl.library.caltech.edu/). These reports contain data on strong-motion recorded in the western United States between 1933 and 1971. A uniformly processed version of these data has been presented in [21] and [189] and has been included in a larger EQINFOS database that covers important strong-motion records in the western United States between 1933 and 1984.[190]

In 1982, EQINFOS (the Strong-Motion Earthquake Data Information System) was launched at USC.[191] Digitized accelerograms and computed spectra were kept on a hard disk at USC, and users could access and download the data using an acoustic modem. This service was popular among earthquake engineers who wanted either to search for a recorded accelerogram with conditions similar to what was required for their projects or to obtain response spectra.

EQINFOS offered (1) convenient routines for users to search the data of their choice; (2) corrected accelerograms and response spectra that could be downloaded, printed, and plotted from a remote location; and (3) the capability for users to submit their acceleration data and process it. The aim of the EQINFOS initiative was to help user with a variety of data formats and processing procedures and to find practical solutions for unifying data formats and data presentations internationally. For example, EQINFOS data were collected, digitizated, and presented for the former Yugoslavia,[67] Bulgaria,[81] and India.[86,87]

In California, the U.S. Geological Survey (USGS, 345 Middlefield Road, Menlo Park, CA 94025, USA), and the Office of Strong-motion Studies (801 K Street, MS 13-35, Sacramento, CA 95814-3531, USA) of the California Division of Mines and Geology (CDMG), now of the California Geological Survey (CGS), issued quick reports with copies of acceleration records recorded following moderate and large earthquakes. For example, for the 1994 Northridge California earthquake see Porcella et al.[192] and Shakal et al.[193]

All strong-motion data digitized and processed at USC and at the USGS are sent to the National Geophysical Data Center (NGDC/NOAA, 325 Broadway, Boulder, CO 80303, USA) for distribution. The office of Strong-Motion Studies of the CGS distributes their data on floppy disks.

The first report presenting strong-motion earthquake records in New Zealand was published by the Physics and Engineering Laboratory of the Department of Scientific and Industrial Research (Private Bag, Lower Hutt, New Zealand). Accelerograms recorded on 35-mm film are enlarged four times, in a sequence of segments, with clearly marked fiducial lines.

The first large strong-motion was recorded in Taiwan on April 14, 1976 during a magnitude 5.4 earthquake. Volume I of the Catalog of Strong-Motion Accelerograph Stations and Records in Taiwan, by the Institute of Earth Sciences, Academia Sinica (Taipei, Taiwan), showing contact copies of SMA-1 70 mm film records, was published in December of 1978.[63]

A catalog describing 5252 strong-motion records in Mexico, for the period 1960 to 1993, was published by the Sociedad Mexicana de Ingenieria Sismica in 1995[194] and is accompanied by digitized data on a CD disk.

6.3 Modern Data Dissemination

With the appearance of the Internet, the possibilities for data distribution have expanded dramatically. At present, the availability of storage, the throughput rates, and the access may still be limited for some users, but during the next several years rapid and efficient access to Web sites that distribute strong-motion data will be within everyone's reach.

6.3.1 Rapid release of strong-motion data

In 1983, the author proposed to the National Science Foundation (NSF) that a system should be developed for remote access to recorded strong-motion data, with two principal objectives: (1) to provide rapid evaluation of the distribution of devastating strong-motion and (2) to enable remote maintenance, calibration and collection of strong-motion records in free-field. Prior experience with the San Fernando, California earthquake of 1971 showed that much confusion could be avoided during the hours immediately following the main shock and that the work of local governments in coordinating the post-earthquake rescue operations would benefit from reliable data on the location and distribution of the damaging levels of strong-motion. The emphasis of this proposal was on saving human life during the hours immediately following the devastating shock, but the possible advantages of developing an early warning system were also stated. In 1984, NSF funded the project, and the System for Interrogation of Field Instruments (SIFI-1) was developed at USC by Dr. Ali Amini in 1986.

SIFI-1 consisted of three circuit boards, including the central processing unit (Zilog 4MHz Z80), a 1,200-baud modem board, and an interface board equipped with a high-speed, 8-bit analog-to-digital converter. SIFI-1 was connected to a SMA-1 accelerograph and could be accessed from a remote terminal or a computer by ordinary telephone lines. Through user-friendly software commands, SIFI-1 provided detailed information on the status of the accelerograph, and gave the time of occurrence and amplitudes of peak recorded strong-motion velocities. There was enough memory to store data on time and on the peak velocities for at least 50 events.[195]

Nine stations in the Los Angeles and Vicinity Strong-Motion Array were equipped with SIFI-1 in late 1987 and operated until 1995 (Fig. 9). Then, the experience of the 1994 Northridge earthquake showed that overall capabilities, efficiency, and wealth of information that can be provided by aerial surveys of damage, conducted by helicopters, from several competing television networks in the Los Angeles metropolitan area surpassed the information on the distribution of peak velocities of damaging strong-motion. Helicopter surveys provided rapid and excellent pictorial descriptions of damage and of all of its consequences, including, for example, the fires triggered by broken gas pipes and electrical lines. Following the Northridge earthquake, we concluded that there are better and more useful ways to use academic research time and funding and chose not to continue the maintenance and further development of the SIFI system. We also concluded that an early warning system for strong-motion shaking in Los Angeles would be of limited use, due to the fact that the majority of potentially damaging earthquakes would occur within the metropolitan area (e.g. like Long Beach, 1933; San Fernando, 1971; and Northridge, 1994), thus providing, at best, a window of only a few seconds to respond. A few seconds is too short for the majority of useful safety-related actions to be implemented before the arrival of strong shaking. Early warning can work well when earthquakes are at a considerable distance from the metropolitan area (e.g., Mexico city) and when it takes one minute or longer for damaging strong-motion waves to arrive.

Real- and near-real-time access to strong-motion data (with emphasis on the distribution of peak ground velocities) and the development of early warning systems nevertheless continue to attract interest and funding for many seismological projects.[78] For example, in Taiwan the Rapid Earthquake Information Release (RTP) program is based on data which are telemetered from 80 strong-motion stations using 4,800-baud leased telephone lines. When the prescribed trigger criteria are satisfied, the data are stored in memory and automatically analyzed.[196] The results are then released to the emergency response agencies, by e-mail, World Wide Web, fax, and a pager system. The data from the Kyoshin Net in Japan (Fig. 13) are distributed via the Internet. The Seismic Alert System of Mexico City is based on 12 digital strong-motion stations located along a 300-km stretch of the Guerero coast, with inter-station spacing of about 25 km. Each field station has a microcomputer that continuously processes the recorded data. When strong-motion is detected, within 10 seconds of its origin time a warning is sent by dual telecommunication systems, one VHF central radio relay station, and three UHF radio stations located between the Guerero coast and Mexico City.[197,198] Other systems for rapid earthquake data distribution are described by Gee et al.[199] and Kanamori et al.[78]

6.3.2 Electronic distribution of processed and archived strong-motion data

Many Web addresses that provide earthquake data are listed by the Pacific Northwest Seismograph Network at http://www.geophys.washington.edu/seismosurfing.html, and for European users they are listed at http://seismo.ethz.ch/seismosurf/seismobig.html.

7. REFERENCES

1. Duke, C.M., et al., Strong earthquake motion and site conditions: Hollywood, *Bull. Seism. Soc. Am*., 60(4), 1271-1289, 1970.

2. Hudson, D.E., Ground motion measurements, in *Earthquake Engineering* Wiegel, R., Ed., Prentice-Hall, Englewood Cliffs, N.J., 07, 1970.

3. Heck, N.H., McComb, H.E. and Ulrich, F.P., Strong-motion program and tiltmeters, in *Earthquake Investigations in California 1934-1935*, Special Publication No. 201, U.S. Dept. of Commerce, Coast and Geodetic Survey, 4-30, 1936.

4. Neumann, F., The analysis of records, in *Earthquake Investigations in California 1934-35*, Special Publication No. 201, U.S. Dept. of Commerce, Coast and Geodetic Survey, 31, 1936.

5. Blume, J.A., The building and ground vibrator, in *Earthquake Investigations in California 1934-1935*, Special Publication No. 201, U.S. Dept. of Commerce, Coast and Geodetic Survey, 117, 1936.

6. Martel, R.R., A report on earthquake damage to type III buildings in Long Beach, *Earthquake Investigation in California 1934-1935*, Special Publication No. 201, U.S. Dept. of Commerce, Coast and Geodetic Survey, 143, 1936.

7. Cloud, W.K. and Carder, D.S., The strong-motion program of the Coast and Geodetic Survey, in *Proc. First World Conference on Earthquake Engineering*, Berkeley, California, 2, 1, 1956.

8. Takahashi, R., The SMAC strong-motion accelerograph and other latest instruments for measuring earthquakes and building vibrations, *in Proc. First World Conf. In Earthquake Engrg*., Berkeley, California, 3, 1, 1956.

9. Halverson, H.T., Modern trends in strong movement (Strong-motion) instrumentation, Dynamic waves in civil eng., *Proc. Conf. Organized by the Society for Earthquake and Civil Eng. Dynamics*, Swansea, Howells, D.A., Haigh, I.P., Taylor, C., Ed., Wiley-Interscience, London, 341, 1970.

10. Trifunac, M.D. and Todorovska, M.I., Recording and interpreting earthquake response of full scale structures, in *NATO Advanced Research Workshop on Strong-motion Instrumentation for Civil Eng. Structures*, Kluwer, Istanbul, 131, 2001.

11. Trifunac, M.D. and Todorovska, M.I., Evolution of accelerographs, data processing, strong-motion arrays and amplitude and spatial resolution in recording strong earthquake ground motion, *Soil Dyn. and Earth. Eng*., 21(6), 537, 2001.

12. Golitsyn, B., *Vorlesungen über Seismometrie*, B.G. Täubner, Leipzig and Berlin, 1914.

13. Berlage, H.P. Jr., Seismometer, in *Handbuch der Geophysik*, 4, Gutenberg, B., Ed., Gebrueder Borntraeger Verlag, Berlin, Chap. 4, 1932.

14. Dewey, J. and Byerly, P., The early history of seismometry (to 1900), *Bull. Seismol. Soc. Am*., 59(l), 183, 1969.

15. Melton, B.S., Earthquake seismograph development: A modern history — part 1, *EOS,* (1981a) 62(21), 505, 1981.

16. Melton, B.S., Earthquake seismograph development: A modern history-part 2, *EOS,* 62(25), 545, 1981.

17. Wenner, F., Development of seismological instruments at the bureau of standards, *Bull. Seism. Soc. Am***.** 22**,** 60, 1932.

18. Ruge, A.C., and McComb, H.E., Tests of earthquake accelerometers on a shaking table, *Bull. Seism. Soc. Am*., 33 (1), 2, 1943.

19. Ruge, A. C., A Machine for Reproducing Earthquake Motions Direct from a Shadowgraph of the Earthquake, Bull. Seism. Soc. Am., 26, 201, 1936.

20. McComb, H.E., and A.C. Ruge, Tests of earthquake accelerometers on a shaking table, *Bull. Seism. Soc. Am*., 27, 325, 1937.

21. Trifunac, M.D. and Lee, V.W., *Uniformly processed strong earthquake ground accelerations in the western united states of America for the period from 1933 to 1971: corrected acceleration, velocity and displacement curves*, Department of Civil Engineering, Report No. 78-01, University of Southern Calif., Los Angeles, California, 1978.

22. Trifunac, M.D., Hudson, D.E., and Brady, A.G., *Strong-motion accelerograms. II corrected acceleration and integrated velocity and displacement curves*, Report EERL 75-52. Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, CA, 1975.

23. Trifunac, M.D. and Brune, J.N., Complexity of energy release during the Imperial Valley, California, earthquake of 1940, *Bull. Seism. Soc. Am*., 60, 137, 1970.

24. Trifunac, M.D. and Hudson, D.E., Analysis of the station No. 2, seismoscope record — 1966 Parkfield, California Earthquake, *Bull Seism. Soc. Am*., 60, 785, 1970.

25. Trifunac, M.D. and Hudson, D.E., Analysis of Pacoima dam accelerogram, San Fernando, California earthquake of 1971, *Bull. Seism. Soc. Am*., 61, 1393, 1971.

26. Strong-Motion Earthquake Observation Committee, *Strong-motion Earthquake Records in Japan*, 1, Earthquake Research Institute, Univ. of Tokyo, 1960.

27. Trifunac, M.D. and Hudson, D.E., *Laboratory evaluation and instrument corrections of strong-motion accelerographs*, Earthquake Eng. Res. Lab., EERL 70-04, Calif. Inst. of Tech., Pasadena, California, 1970.

28. Hudson, D.E., History of accelorgraph development, in *Proc. Golden Anniversary Workshop on Strong-motion Seismometry*, Univ. of Southern California, Los Angeles, California, 29, 1983.

29. Golitsyn, B.B., Lektsii, po Seysmometrii (Lectures on Seismometry), Sib. Izd. Rossiyskoy Akad. Nauk, Moskva, 1912.

30. Novikova, E.I. and Trifunac, M.D., *Instrument correction for the coupled transducer-galvanometer systems*, Dept. of Civil Eng., Report No. CE 91-02, Univ. Southern California, 1991.*

31. Medvedev, S.V., *Inzenernaya Seismologiya*, State Publishing of the Civil Engineering, Architectural and Building Materials Literature, Moscow, (in Russian), 1962.

32. Borisevich, E.S., Editor, Katalog Geofizicheskoi Apparaturi, Nauka, Moscow, (in Russian), 1981.

33. Lee, V.W. and Wang, Y.Y, On the instrument correction of the RDZ-1 strong-motion pendulum galvanometer in China, *Earthquake Eng. and Eng. Vibr*., 3, (4), 25, (in Chinese), 1983.

34. Golitsyn, B., Uber eine Dynamische Skala zur Schätzung von Makroseismischen Bewegungen, St. Petersburg, Review by H. O. Wood, in *Bull. Seism. Soc. Am*., 3, 90, 1913.

35. Kirkpatrick, P., Seismic measurements by the overthrow of columns, *Bull. Seism. Soc. Am*., 17, 95, 1927.

36. Suyehiro, K., A seismic vibration analyzer and the records obtained therewith, *Bull. Earthquake Res. Inst*., Tokyo Univ., 1, 59, 1926.

37. Suyehiro, K., Engineering seismology notes on American lectures, *Proc. ASCE*, 58(4) 1, 1932.

38. Ulrich, F. P., Progress report for 1939 of the seismological field survey of the U.S. Coast and Geodetic Survey, *Bull. Seism. Soc. Am*., 31, 107, 1941.

39. Medvedev, S.V., Novaya seismicheskaya Shkala, Trudy Geofizicheskogo Instituta AN SSSR, No 21, 1953.

40. Medvedev. S. V., *Elementary Seismology*, Israel Program for Scientific Translations, Jerusalem, 1965.

41. Hudson, D.E., *The Wilmot survey type strong-motion earthquake recorder*, Earthquake Eng. Res. Lab., California Inst. of Tech., Pasadena, 1958.

42. Krishna, J. and Chandrasekaran, A. R., Structural response recorders, in *Proc. Third World Conf. on Earthquake Eng.,* New Zealand, 143, 1965.

43. Fournier d'Albe, E. M., Report on proceedings of international symposium on strong earthquake motion, Mexico City, August, 1972, *Bull. Seism. Soc. Am.,* 63, 1857, 1973.

44. Trifunac, M.D., An Instrumental comparison of the Modified Mercalli (MMI) and Medvedev-Karnik-Sponheuer (MKS) intensity scales, *in Proc. Sixth World Conf. on Earthquake Eng*., New Delhi, India, I, 715, 1977.

45. Cloud, W. K. and Hudson, D. E., A simplified instrument for recording strong-motion earthquakes, *Bull. Seism. Soc. Am.,* 51, 159, 1961.

46. Hudson, D. E. and Cloud, W. K., An analysis of seismoscope data from the Parkfield earthquake of June 27, 1966, *Bull. Seism. Soc. Am*., 57, 1143, 1967.

47. Hudson, D.E., *Strong-Motion Instrumental Data on the San Fernando Earthquake of February 9, 1971*, Earthquake Eng. Res. Lab., California Inst. of Tech. and Seismological Field Survey, NOAA, 1971.

48. Scott, R.F., The calculation of horizontal accelerations from seismoscope records, *Bull. Seism. Soc. Am*., 63, 1637, 1973.

49. Trifunac, M.D., and Brady, A.G., On correlation of seismoscope response with earthquake magnitude and Modified Mercalli Intensity, *Bull. Seismol. Soc. Amer*., 65(2), 307, 1975.

50. Trifunac, M.D. Statistical analysis of the computed response of structural response recorders (SRR) for accelerograms recorded in the United States of America, *Proc. Sixth World Conf. on Earthquake Eng*., New Delhi, India, III, 2956, 1977.

51. Hudson, D.E., *Reading and Interpreting Strong-Motion Accelerograms*, Earthq. Eng. Res. Inst. Monograph, Berkeley, California, 1979.

52. Trifunac, M.D. Tectonic stress and source mechanism of the Imperial Valley, California earthquake of 1940, *Bull. Seism. Soc. Amer*., 62, 1283, 1972.

53. Halverson, H., The strong-motion accelerograph, in *Proc. Third World Conf. on Earthquake Eng*., 1, III, 75, 1965.

54. Trifunac, M.D., Udwadia, F.E. and Brady, A.G., *High-Frequency Errors and Instrument Corrections of Strong-Motion Accelerogram*, Earthq. Engrg. Res. Lab. EERL 71-05, Calif. Inst. of Tech., Pasadena, California, 1971.

55. Trifunac, M.D. and Lee, V.W., *Automatic Digitization and Processing of Strong-Motion Accelerograms*, I and II, Dept. of Civil Eng. Rep. No. 79-15, Univ. of Southern California, Los Angeles, California, 1979.

56. Lee, V.W., Trifunac, M.D. and Amini, A., Noise in Earthquake Accelerograms, *ASCE*, *EMD*, 108, 1121, 1982.

57. Amini, A., Trifunac, M.D., and Nigbor, R.L., A note on the noise amplitudes in some strong-motion accelerographs, *Soil Dyn. and Earthquake Eng*., 6(3), 180, 1987.

58. Trifunac, M.D., Todorovska, M.I. and Lee, V.W., Common problems in automatic digitization of strong-motion accelerograms, *Soil Dynamics and Earthquake Eng*., 18(7), 519, 1999.

59. Hudson, D.E., Dynamic tests of full-scale structures, in Earthquake Engineering, Wiegel, R., Ed., Prentice-Hall, Englewood Cliff, N.J., 127, 1970.

60. Diehl, J.G. and Iwan, W.D., A Technical review of modern strong-motion accelerographs, in *Proc. Tenth world conf. on Earthquake Eng*., Balkema, Rotterdam, 1, 169, 1992.

61. Skinner, R.I., et al., *Strong-motion Earthquake Records in New Zealand, 1, January 1965 to December 1970,* Physics and Engineering Lab., Dept. of Scientific and Industrial Research, New Zealand, 1971.

62. Skinner, R.I., et al., *Strong-motion Earthquake Records in New Zealand*, *3, January 1972 to December 1972*, Physics and Engineering Lab., Dept. of Scientific and Industrial Research, New Zealand 1975.

63. Chiu, H.C. and Liu, W.S., *Catalog of Strong-motion Accelerograph Stations and Records in Taiwan*, I, Instit. of Earth Sciences, Academia Sinica, Taipei, Taiwan 1978.

64. Shin, T.C., Progress summary of the Taiwan strong-motion instrumentation program, in *Symposium on the Taiwan Strong-Motion Program*, Central Weather Bureau, 1, 1993.

65. Loh, C.H., Penzien, J.,Tsai, Y.B., Engineering analysis of SMART 1 array accelerograms, *Int. J. Earthquake Eng. Struct. Dyn.,* 10, 575, 1982.

66. Huang, H.C., and Chiu, H.C., Estimation of Site Amplification from Dahan Downhole Recording, *Int. J. Earthquake Eng. Struct. Dyn*., 25, 319, 1996.

67. Jordanovski, LR., et al., *Strong Earthquake Ground Motion Data in EQINFOS: Yugoslavia*, 1, Dept. of Civil Eng. Rep. No. 87-05, Univ. of Southern California, Los Angeles, California, 1987.*

68. Haskell, N.A., Elastic displacements in the near field of a propagating fault, *Bull. Sesm. Soc. Am.*, 59, 865, 1969.

69. Trifunac, M.D., A three-dimensional dislocation model for the San Fernando, California, Earthquake of February 9, 1971, *Bull. Seism. Soc. Am.*, 64, 149, 1974.

70. Trifunac, M.D. and Udwadia, F.E., Parkfield, California, earthquake of June 27, 1966: A three-dimensional moving dislocation, *Bull. Seism. Soc. Am.*, 64, 511, 1974.

71. Jordanovski, L.R., Trifunac, M.D., Lee, V.W., *Investigation of Numerical Methods in Inversion of Earthquake Source Mechanism*, Dept. of Civil Engrg. Report No. 86-01, Univ. of Southern California, Los Angeles, California, 1986.*

72. Jordanovski, L.R. and Trifunac, M.D., Least Square Model with Spatial Expansion: Application to the Inversion of Earthquake Source Mechanism, *Soil Dyn. and Earthquake Engrg.*, 9(6), 279, 1990.

73. Jordanovski, L.R. and Trifunac, M.D. Least-Square Inversion with Time Shift Optimization and an Application to Earthquake Source Mechanism, *Soil Dyn. and Earthquake Engrg.*, 9(5), 243, 1990.

74. Jordanovski, L.R. and Todorovska, M.I., Inverse studies of the earthquake source mechanism from near field strong-motion records, *ISET Journal*, 39(1-2), 73, 2002.

75. Dielman, R.J., Hanks, T.C. and Trifunac, M.D., An array of strong-motion accelerographs in Bear Valley, California, *Bull. Seism. Soc. Am.*, 65, 1, 1975.

76. Lee, W.H.K., et al., CWB free-field strong-motion data from the 21 September, Chi-Chi, Taiwan, earthquake, *Bull. Seism. Soc. Am.*, 91(5), 1370, 2001.

77. Kinoshita, S., Kyoshin net (K-NET). *Seism. Res. Lett.*, 69, 309, 1998.

78. Kanamori, H., Hauksson, E., and Heaton, T., Real-time seismology and earthquake hazard mitigation, *Nature*, 390, 461, 1997.

79. Wald, D. J., et al., Triniet "ShakeMaps": Rapid generation of peak around motion and intensity maps for earthquakes in southern California., *Earthquake Spectra*, 15(3), 537, 1999.

80. Rosas, J.S., Strong-motion accelerograms processing at the National Institute of Seismic Hazard Prevention in Argentina, *Bull. Int. Inst. of Seism. and Earthquake Eng*, 20, Special Issue, 21, 1983.

81. Nenov, D., Georgiev, G. and Paskaleva, I., *Strong Earthquake Ground Motion Data in EQINFOS: Accelerograms Recorded in Bulgaria*, Lee, V.W. and Trifunac, M.D., Ed. Dept. of Civil Eng. Report No. 90-02, Univ. of Southern California, Los Angeles, California, 1990.*

82. Milne, W.G. and Rogers, G.C., Development of strong-motion seismographs in western Canada, in *Proc. Fifth World Conf. on Earthquake Eng*., Rome Italy, 1, 1042, 1973.

83. Midorikawa, S., Riddell, C. and Cruz, E.F., *Strong-motion Array Observation in Santiago, Chile (SMASCH Array*), DIE 90-2, Depto. de Ingenieria Estructural, Pontifica Univ. Catalica de Chile, Santiago, Chile, 1990.

84. Bommer, J.J., et al., A new digital accelerograph network for El Salvador, *Seism. Res. Lett*., 68(3), 426, 1997.

85. Makropoulos, K.C. and Diagourtas, D., The Corinthian Gulf (Greece) Strong-Motion Data Bank: European Seismic Design Practice, Research and Application*, in Proc. Fifth SECED Conference*, Balkema, Rotterdam, 317-322, 1995.

86. Gupta, I.D., Rambabu, V. and Joshi, R. G*., Strong Earthquake Ground Motion Data in EQINFOS for India*: *1A*, Trifunac, M.D., Todorovska, M.I. and Lee, V.W., Eds. Dept. of Civil Eng. Rep. No. 93-03, Univ. of Southern California, Los Angeles, California, 1993.*

87. Chandrasekaran, A.R. and Das, J.D., *Strong Earthquake Ground Motion Data in EQINFOS for India: 1B*, Trifunac, M.D., Todorovska, M.I. and Lee, V.W., Eds. Dept. of Civil Eng. Rep. No. 93-03, Univ. of Southern California, Los Angeles, California, 1993.*

88. Chandrasekaran, A.R., Strong-motion Arrays in India, in *Proc. Ninth World Conf. on Earthquake Eng*., VIII, 131, 1988.

89. Iaccarino, E. and Zaffiro, C., Studies of a network of strong-motion accelerographs to be installed in Italy, *Proc. Fifth World Conf. on Earthquake Eng*., Rome, Italy, 1, 1038, 1973.

90. Ohtani, K. and Takahashi, H., The history and status of strong-motion earthquakes in Japan, NIST SP776, wind and seismic effects, in *Proc. 21st Joint Meeting of U.S.-Japan Cooperative program in Natural Resources Panel on Wind and Seismic Effects*, National Inst. of Standards and Technology, Gaithersburg, MD, 172, 1989.

91. Tanaka, T., et al., An observation network of earthquake strong-motions in Suruga Bay region of the Izu Peniusula, *Proc. Eight World Conf. on Earthquake Eng*., II, 15, 1984.

92. Okawa, I., Kashima, T., and Koyama, S., Dense instrumentation in BRI building and surrounding ground, in *Proc. UJNR Workshop on Soil-Structure Interaction*, USGS Open File Report 99-142, 22, 1, 1999.

93. Anderson, J.G. and Quaas, R., Guerreso strong-motion array, in *Proc. Ninth World Conf. Earthquake Eng*., VIII, Paper SB-5, 143, 1988.

94. Berrill, J.B., Suggested extensions of the New Zealand strong-motion accelerograph network, *Bull. New Zealand Nat. Soc. for Earthquake Eng*., 12(3), 264, 1979.

95. Cousins, W.J., *Ground condition at Strong-Motion Recording Sites in New Zealand,* Seismic Report, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand, 1996.

96. Hefford, R.T. and Randel, P.M., Procedures for operating the New Zealand strong-motion accelerograph network, *Bull. New Zealand Soc. for Earthquake Eng.*, 16(1), 45, 1983.

97. Skinner, R.I., Stephenson, W.R., and Hefford, R.T., Strong-motion earthquake recording in New Zealand, *Bull. New Zealand Soc. for Earthquake Eng*., 4(1), 31, 1971.

98. Smit, P., *Swiss national strong-motion network, Strong-motion Bulletin, October 1993 – September 1994*, Publ. Series of the Swiss Seismological Service, Federal Institute of Technology, No. 107, Zurich, Switzerland, 1994.

99. Liu, K-S., Shin, T-C., and Tsai, Y-B., A free-field strong-motion network in Taiwan, *Terr., Atmos., and Oceanic Sci*., 10(2), 377, 1999.

100. Malaver, A. and Chacon, C., Venezuelan strong-motion accelerograph network, in *Proc. Eighth World Conf. on Earthquake Eng*., II, 7, 1984.

101. Knudson, C., Present day status of world wide strong-motion instruments, in *Proc. Fifth World Conf. on Earthquake Eng*., Rome, Italy, 1, 1028, 1973.

102. Trifunac, M.D., Surface motion of a semi-cylindrical alluvial valley for incident Plane SH Waves, *Bull. Seism. Soc. Am*., 61, 1755, 1971.

103. Trifunac, M.D., Hao, T.Y., and Todorovska, M.I., On reoccurrence of site specific response, *Soil Dynamics and Earthquake Eng*., 18(8), 569, 1999.

104. Trifunac, M.D. and Ivanović, S.S., Reocurrence of site specific response in former Yugoslavia — Part I: Montenegro, *Soil Dyn. and Earthquake Eng*., 23(8) 637, 2003.

105. Trifunac, M.D. and Ivanović, S.S. Reocurrence of site-specific response in former Yugoslavia — Part II: Friuli, Banja Luka and Kopaonik, *Soil Dyn. and Earthquake Eng*., 23(8) 637, 2003.

106. Todorovska, M.I. and Trifunac, M.D., Amplitudes, polarity, and time of peaks of strong-motion during the 1994 Northridge, California, Earthquake, *Soil Dyn. and Earthquake Eng*., 16(4), 235, 1997.

107. Todorovska, M.I. and Trifunac, M.D., Distribution of pseudo-spectral velocity during the Northridge, California, Earthquake of 17 January, 1994, *Soil Dyn. and Earthquake Eng*., 16(3), 173, 1997.

108. Todorovska, M.I., et al., The $M_L = 6.4$ *Northridge, California, earthquake and five M > 5 aftershocks between 17 January and 20 March 1994 — Summary of processed strong-motion data, Dept*. of Civil Eng. Report 99-01, Univ. of Southern California, Los Angeles, California, 1999.*

109. Trifunac, M.D. and Todorovska, M.I., Nonlinear soil reponses — 1994 Northridge California, earthquake*, J. Geotech. Eng*., *ASCE*, 122(9), 725, 1996.

110. Trifunac, M.D. and Todorovska, M.I., Northridge, California, earthquake of January 17, 1994: Density of red-tagged buildings versus peak horizontal velocity and site intensity of strong-motion, *Soil Dyn. and Earthquake Eng.*, 16(3), 209, 1997.

111. Trifunac, M.D. and Todorovska, M.I., Northridge, California, earthquake of 17 January 1994: Density of pipe breaks and surface strains, *Soil Dyn. and Earthquake Eng*., 16(3), 193, 1997.

112. Trifunac, M.D. and Todorovska, M.I., Nonlinear soil response as a natural passive isolation mechanism – the 1994 Northridge, California earthquake, *Soil Dyn. and Earthquake Eng*., 17(1), 41, 1998.

113. Trifunac, M.D. and Todorovska, M.I., The Northridge, California, earthquake of 1994: Fire ignition by strong shaking, *Soil Dyn. and Earthquake Eng*., 17(3), 165, 1998.

114. Trifunac, M.D. and Todorovska, M.I., Damage distribution during the 1994 Northridge, California, earthquake, Relative to generalized categories of surficial geology, *Soil Dyn. and Earthquake Eng*., 17(4), 239, 1998

115. Trifunac, M.D. and Todorovska, M.I., Amplification of strong ground motion and damage patterns during the 1994 Northridge, California, earthquake, in *Proc. ASCE Specialty Conf. on Geotechnical Earthquake Eng. and Soil Dynamics*, Seattle, Washington, Geotechnical Special Publ. No. 75, ASCE, 1, 714, 1998.

116. Trifunac, M.D. and Todorovska, M.I., Reduction of structural damage by nonlinear soil response, *J. Struct. Eng*., ASCE, 125(1), 89, 1999.

117. Trifunac, M.D. and Todorovska, M.I., Can aftershock studies predict site amplification factors — Northridge California earthquake of 17 January 1994, *Soil Dyn. and Earthquake Eng*., 19(4), 233, 2000.

118. Trifunac, M.D., and Todorovska, M.I., Long Period Microtremors, Microseisms and Earthquake Damage: Northridge, California Earthquake of 1994, *Soil Dynamics and Earthquake Eng*., 19(4), 253, 2000.

119. Trifunac, M.D., Todorovska, M.I. and Ivanović, S.S, A note on distribution of uncorrected peak ground accelerations during the Northridge, California, earthquake of 17 January 1994, *Soil Dyn. and Earthquake Eng*., 13(3), 187, 1994.

120. Trifunac, M.D., Todorovska, M.I. and Ivanović, S.S., Peak velocities, and peak surface strains during Northridge, California, earthquake of 17 January 1994, *Soil Dyn. and Earthquake Eng*., 15(5), 301, 1996.

121. Trifunac, M.D.,Todorovska, M.I. and Lee, V.W., The Rinaldi strong-motion accelerogram of Northridge, California, earthquake of 17 January 1994, *Earthquake Spectra*, 14(1), 225, 1998.

122. Trifunac, M.D., Todorovska, M.I., and Ivanović, S.S., *Seven-storey reinforced concrete building in Van Nuys California: Strong-motion data recorded between 7 February 1971 and 9 December 1994, and description of damage following Northridge, 17 January 1994 earthquake*, Dept. of Civil Eng., Report No. 99-02, Univ. of Southern California, Los Angeles, California, 1999.*

123. Trifunac, M.D. Ivanović, S.S., and Todorovska, M.I., Apparent periods of a building, Part I: Fourier analysis, *J. of Struct. Eng*., *ASCE*, 127 (5) 517, 2001.

124. Trifunac, M.D. Ivanović, S.S. and Todorovska, M.I., Apparent periods of a building, part II: Time-frequency analysis, *J. of Struct. Eng*., *ASCE*, 127(5) 527, 2001.

125. Trfiunac, M.D. and Ivanović, S.S., *Analysis of drifts in a seven-storey reinforced concrete structure*, Dept. of Civil Eng., Report No. CE 03-01, Univ. of Southern California, Los Angeles, California, 2003.*

126. Trifunac, M.D., Hao, T.M., and Todorovska, M.I., *Response of a 14 storey reinforced concrete structure to excitation by nine earthquakes: 61 years of observation in the Hollywood storage building*, Dept. of Civil Eng. Rep. No. CE 01-02, Univ. of Southern California, Los Angeles, California, 2001.*

127. Todorovska, M.I., Cross-axis sensitivity of accelerographs with pendulum-like transducers — Mathematical model and the inverse problem, *Earthquake Eng. and Struct. Dyn*., 27(10), 1031, 1998.

128. Todorovska, M.I., et al., Advanced accelerograph calibration of the Los Angeles Strong-motion array, *Earthquake Eng. and Struct. Dyn*., 27(10), 1053, 1998.

129. Luco, J.E. Wong, H.L., and Trifunac, M.D., *Soil-structure interaction effects on forced vibration tests*, Dept. of Civil Eng., Rep. No. 86-05, Univ. of Southern California, Los Angeles, California, 1986.*

130. Kojić, S., Trifunac, M.D. and Anderson, J.C., *A post-earthquake response analysis of the Imperial County services building*, Dept. of Civil Engrg, Report No. 84-02, Univ. of Southern California, Los Angeles, California, 1984.*

131. Todorovska, M.I., Ivanović, S.S., and Trifunac, M.D., Wave propagation in a seven-storey reinforced concrete building, part I: Theoretical Models, *Soil Dyn. and Earthquake Eng*., 21 (3) 211, 2001.

132. Todorovska, M.I., Ivanović, S.S., and Trifunac, M.D., Wave propagation in a seven-storey reinforced concrete building, part II: Observed Wave Numbers, *Soil Dyn. and Earthquake Eng*., 21 (3) 225, 2001.

133. Ivanović, S.S., and Trifunac, M.D., *Ambient vibration survey of full-scale structures using personal computers (with examples in Kaprielian Hall),* Dept. of Civil Eng., Rep. No. 95-05, Univ. of Southern California, Los Angeles, California, 1995.*

134. Ivanović, S.S., Trifunac, M.D., and Todorovska, M.I., On identification of damage in structures via wave travel times, *NATO Advanced Research Workshop on Strong-motion Instrumentation for Civil Engineering Structures*, June 2 — 5, 1999, Istanbul, Kluwer, Acad. Publ., Netherlands, 2001.

135. Ivanović, S.S., et al., *Two ambient vibration tests of a seven storey reinforced concrete building damaged by Northridge 1994 earthquake*, Dept. of Civil Eng. Rep. No. 99-03, Univ. of Southern California, Los Angeles, California, 1999.*.

136. Udwadia, F.E., Uniqueness problems in structural identification from strong-motion records, in *Proc. Sixth World Conf. on Earthquake Eng., India*, II, 1010, 1977.

137. Safak, E., Detection of seismic damage in multi-storey buildings by using wave propagation analysis, in *Proc. Sixth U.S. National conf. on Earthquake Eng*., Seattle, Washington, 1998.

138 Udwadia, F.E. and M.D. Trifunac, Time- and amplitude-dependent response of structures, *Earthquake Engrg and Struct. Dyn*., 2, 359, 1974.

139. Moslem, K. and Trifunac, M.D., *Effects of soil-structure interaction on the response of buildings during strong earthquake ground motions*, Dept. of Civil Eng., Report No. 86-04, Univ. of Southern California, Los Angeles, California, 1986.*

140. Todorovska, M.I. and Trifunac, M.D., *Radiation damping during two-dimensional in-plane building-soil interaction*, Dept. of Civil Eng., Report No. 91-01, Univ. of Southern California, Los Angeles, California, 1991.*

141. Todorovska, M.I. and Trifunac, M.D., Anti-plane earthquake waves in long structures, *J. Eng. Mech*., *ASCE*, 115(2), 2687, 1989.

142. Todorovska, M.I. and Trifunac, M.D., Propagation of earthquake waves in buildings with soft first floor, *J. Eng. Mech*., *ASCE*, 116(4), 892, 1990.

143. Todorovska, M.I. and Trifunac, M.D., *Analytical model for the in-plane building-foundation-soil interaction: Incident P-, SV-, and Rayleigh Waves*, Dept. of Civil Eng., Report No. 90-01, Univ. of Southern California, Los Angeles, California, 1990.*

144. Trifunac, M.D. and Lee, V.W., *Routine computer processing of strong-motion accelerograms*, Earthquake Eng. Res. Lab., EERL 73-03, Calif. Inst. of Tech., Pasadena, California, 1973.

145. Lee, V.W. and Trifunac, M.D., *Automatic digitization and processing of accelerograms using personal computers*, Dept. of Civil Eng., Rep. No. 90-03, Univ. of Southern California, Los Angeles, California, 1990.*

146. Trifunac, M.D. and Lee, V.W., Peak surface strains during strong earthquake motion, *Soil Dyn. and Earthquake Eng*., 15(5), 311, 1996.

147. Housner, G.W. and Brady, A.G., Natural periods of vibrations of buildings, *J. Eng. Mech. Div*., *ASCE*, 89(4), 31, 1963.

148. Goel, R.K. and Chopra, A.K., Period formulas for concrete shear wall buildings, *J. Struct. Eng*., *ASCE*, 124(4), 426, 1998.

149. Trifunac, M.D., Comments on "Period Formulas for Concrete Shear Wall Buildings," *J. of Struct. Eng*., *ASCE*, 125(7), 797, 1999.

150. Trifunac, M.D., Comments on "Seismic soil-structure interaction in buildings," paper I: analytical methods (paper No. 16525), and paper II: Empirical findings (paper No. 16526), *J. Geotech. and Geoenvir. Eng*., *ASCE*, 126(7), 668, 2000.

151. Graizer, V.M., On inertial seismometry, Izvestiya, Earth Physics, A. N. SSSR, 25(1), 26, 1989.

152. Trifunac, M.D. and Todorovska, M.I., A note on the useable dynamic range in accelerographs recording translation, *Soil Dyn. and Earthquake Eng*., 21(4) 275, 2001.

153. Neumann, F., Analysis of strong-motion seismograph record of the western Nevada earthquake of January 30, 1934, with description of a method of analyzing

seismograms by precise integration, U. S. Coast and Geod. Surv., Strong-motion Report No. 4, pp. 22 (mimeographed), 1934.

154. Neumann, F., An appraisal of numerical integration methods as applied to strong-motion data, *Bull. Seism. Soc. Am*., 33 (1), 21, 1943.

155. Ruge, A.C., Discussion of principal results from the engineering standpoint, *Bull Seis. Soc. Am*. 33 (1) 13, 1943.

156. Neumann, F., A mechanical method of analyzing accelerograms, *Trans. Am. Geophys. Union, 17th Ann. Mtg*., (illus.), 1936.

157. Neumann, F., *The simple torsion-pendulum as an accelerogram analyzer*, Publ. du Bur. Centr. Seis. Internat., Ser A, Travaux Sci., fasc. 15, 1937.

158. Blake, A. The results of strong-motion measurements, *Earthquake Notes* and *Abstr. of the Proc. 1935 Meeting, Eastern Section, Seism. Soc. Am.,*10, 1935.

159. Biot, M., A mechanical analyzer for the prediction of earthquake stresses, *Bull. Seism. Soc. Amer*., 31(2), 151, 1941.

160. Biot, M.A., Theory of elastic systems vibrating under transient impulse with an application to earthquake-proof buildings, in *Proc. Nat. Acad. Sc*., 19(2), 262, 1933.

161. Biot, M.A., Theory of vibration of buildings during earthquakes, *Z.A.M.M., Bd. 14, Heft 4*, 213, 1934.

162. Biot, M., Analytical and experimental methods in engineering seismology, *Trans. Am. Soc. Civ. Eng*., Paper No. 2183, 1942.

163. Trifunac, M.D., 70th Anniversary of Biot spectrum, 23rd annual ISET lecture, *Indian Soc. of Earthquake Tech. J.* ,40(1), 19-50, 2003.*

164. Converse, A., AGRAM: *A series of computer programs for processing digitized strong-motion accelerograms*. Open-File Report 84-525, U.S. Geological Survey, Menlo Park, 1984.

165. Iai, S., Kurata, E., and Tsuchida, H., *Digitization and correction of strong-motion accelerograms*, Technical Note 286, Port and Harbor Research Institute, Yokosuka, Japan, 1978.

166. Berardi, R., Longhi, G., and Rinaldis, D., Qualification of the European strong-motion databank: Influence of the accelerometric station response and pre-processing techniques, *J. European Earthquake Engineering*, 2, 38, 1991.

167. Hudson, D.E., Brady, A.G. and Trifunac, M.D., *Strong-motion earthquake accelerograms, digitized and plotted data, vol. I*, EERL 70-20, Calif. Inst. of Tech., Pasadena, California, 1969.

168. McComb H.E. and Wenner, F., Shaking-table investigations of teleseismic seismometers, *Bull. Seism. Soc. Am*., 26, 291, 1936.

169. Carder, D.S., *Vibration Observations*, Chapter 5: Earthquake investigations in California 1934 — 1935. Special Publication No. 201, U.S. Dept. of Commerce, Coast and Geodetic Survey, 49, 1936.

170. Amini, A. and Trifunac, M.D., *Analysis of a feedback transducer*, Dept of Civil Eng. Rep No. 83-03, University Southern California, Los Angeles, California, 1983.*

171. Amini, A., Trifunac, M.D. Analysis of force balance accelerometer, *Soil Dyn. and Earthquake Eng*., 4(2): 83, 1985.

172. Wong, H.L., Trifunac, M.D. Effects of cross-axis sensitivity and misalignment on response of mechanical-optical accelerographs. *Bull Seism. Soc. Am*., 67, 929, 1977.

173. Graizer, V.M. On the determination of displacement from strong-motion accelerograms, in *Proc. of Seventh World Conference on Earthquake Eng*., Istanbul, 2,391,1980.

174. Aki, K. and Richards, P., *Quantitative Seismology*, W.H. Freeman, San Francisco, 1980.

175. Todorovska, M.I., et al., *Correction for misalignment and cross-axis sensitivity of strong earthquake motion recorded by SMA-1 accelerographs*, Dept. of Civil Eng. Report No. 95-06, Univ. Southern California, Los Angeles, California, 1995.*

176. Finn, W.E.L. Permanent deformations in ground and earth structures during earthquakes, in *Proc. Ninth World Conf. on Earthquake Eng*., Tokyo-Kyoto, VIII, 201, 1988.

177. Hamada, M. and Saito, K., Earthquake damage by liquefaction-induced permanent ground displacement. in *Proc. Ninth World Conf. on Earthquake Eng*., Tokyo-Kyoto, VIII, 213, 1988.

178. Trifunac, M.D., A note on correction of strong-motion accelerograms for instrument response. *Bull Seism Soc. Am*., 62, 401, 1972.

179. Novikova, E.I. and Trifunac, M.D., Digital instrument response correction for the force balance accelerometer, *Earthquake Spectra*, 8(3), 429, 1992.

180. Trifunac, M.D., Zero-baseline correction of strong-motion accelerograms, *Bull. Seism. Soc. Am*., 61, 1201, 1971.

181. Lee, V.W. and Trifunac, M.D., *Current developments in data processing of strong-motion accelerograms*, Dept. of Civil Engineering, Report No. CE 84-01, University of Southern Calif., Los Angeles, California, 1984.*

182. Hudson, D.E., et al., *Strong-motion earthquake accelerograms II: Corrected accelerograms and integrated velocity and displacement curves*, Earthquake Engineering Research Laboratory, EERL 71-51, California Institute of Technology, Pasadena, 1971.

183. Lee, V.W., A new fast algorithm for calculation of response of a single-degree-of-freedom system to arbitrary load in time, Soil *Dyn. and Earthquake Eng.,* 3, (4), 191, 1984.

184. Lee, V.W., Efficient algorithm for computing displacement, velocity, and .acceleration responses of an oscillator to arbitrary ground motion, *Soil Dyn. and Earthquake Eng.*. 9(6) 288, 1990.

185. Nigam, N.C.and Jennings, P.C., *Digital calculation of response spectra from strong-motion earthquake records*, Earthquake Eng. Res. Lab., California Institute of Technology, Pasadena, 1968.

186. Public Works Research Institute, *Strong-Motion Earthquake Records from Public Works in Japan (1968),* The Public Works Research Institute, Ministry of Constructions, Annual Report No. 3, 1969.

187. Hudson, D.E., Trifunac, M.D., and Brady, A.G. *Strong accelerograms, III: Response spectra*, Earthquake Engineering Research Laboratory, EERL 72-80, California Institute of Technology, Pasadena, 1972.

188. Hudson, D.E., Trifunac, M.D., Udwadia, F.E., and Vijayaraghavan, A., *Strong-motion earthquake accelerograms, IV: Fourier spectra*, Earthquake Engineering Research Laboratory, EERL 72-100, California Institute of Technology, Pasadena, 1972.

189. Trifunac, M.D., *Uniformly Processed strong earthquake ground accelerations in the western United States of America for the Period from 1933 to 1971: Pseudo relative velocity spectra and processing noise*, Department of Civil Engineering, Report No. CE 77-04. University of Southern Calif., Los Angeles, California, 1977.*

190. Lee, V.W. and Trifunac, M.D., *Strong earthquake ground motion data in EQUINFOS*: Part I, Department of Civil Engineering, Report No. 87-01, University of Southern California, Los Angeles. California, 1987.*

191. Lee, V.W. and Trifunac, M.D., *EQUINFOS (The strong-motion earthquake data information system)*, Department of Civil Engineering, Report No. 82-01, University of Southern Calif., Los Angeles, California, 1982.*

192. Porcela, R.L., et al., *Accelerograms recorded at USGS national strong-motion network stations during the M_s = 6.6 Northridge, California earthquake of January 17, 1994,* Open File Report 94-141, U.S. Geological Survey, Department of the Interior, 1994.

193. Shakal, A., et al.., *CSMIP strong-motion records from the Northridge, California earthquake of 17 January 1994,* Report No. OSMS 94-07, California Dept. of Conservation, division of Mines and Geology, Sacramento, California, 1994.

194. Quaas, R.W., et al., *Base nacional de datos de sismos fuertas, catalogo de acelerogramas 1960-1993*, Sociedad Mexicana de Ingenieria Sismica, AC, Camino a Santa Teresa 187, Villa Olimpica Miguel Hidalgo 14020, Mexico D.F., 1995.

195. Amini, A. and Trifunac, M.D., Remote Testing and Interogation of Strong-motion Accelerographs, Tehran, I.R. Iran, in *Proc. First International Conf. on Seismology and Earthquake Eng.*, III, 75.

196. Wu, Y M., et al., Performance of the Taiwan rapid earthquake information release system (RTD) during the 1999 Chi-Chi (Taiwan) earthquake. *Seism. Res. Lett.*, 71, 338, 2000.

197. Espinosa-Aranda, et al., Mexico City seismic alert system, *Seism. Res. Lett.*, 66, 42, 1995.

198. Espinosa-Aranda, et al., Results of the Mexico City early warning system, in *Proc. 11th World Conf. on Earthquake Eng.*, Paper No. 2132, 1996.

199. Gee, L., et al., the rapid earthquake data integration system, *Bull. Seism. Soc. Am.*, 86, 936, 1996

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