STRONG MOTION ACCELEROGRAPH SELECTION

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SUMMARY

Several distinct accelerograph types are available now to meet the requirements of local, strong motion earthquake recording in such diverse applications as regional seismicity, microzonation, high rise buildings, bridges, dams, offshore platforms, and power plants. And the recent development of digitally recording instruments enables certain engineering seismology objectives to be achieved as well. It is the principal object of this paper to discuss and compare the available instrument types and the applications for which they are suited.

ACCELEROGRAPH DESCRIPTIONS

Introduction

Development of the U.S. Coast and Geodetic Standard Seismograph (Ref.1) in 1931 and the resulting records of strong, local acceleration versus time gave engineers access to actual response data with the promise that seismic engineering procedures more and more could be based on actual observations. High cost and limited production prevented widespread dispersion of the Standard Seismograph, but many valuable records were taken, notably Long Beach, 1933; Helena, 1935; El Centro, 1940; Olympia, 1965. Several of the original and later versions are installed and in operating condition in the U.S. and Latin America, though they are being replaced gradually by more modern instruments.

The acquisition of strong motion records from diverse soil, foundation and structural types has been very slowly realized, for it was not until 1963 when, at the urging of the California Institute of Technology earthquake engineering staff, United Electrodynamics, Pasadena, California began development of the AR-240 Strong Motion Accelerograph. At $4995 the AR-240 price was about half the nominal price of the Standard Seismograph. Subsequent significant developments have been the C & GS Mark II Accelerograph (70mm) photofilm), RFT-250 (1967, 70mm photofilm and produced commercially), SMA-1 (1969, folded light path; compact; internal vertical trigger) (Ref.2), RMT-280 (1968, FM analog tape recorder), DSA-1 (1976, digital cassette recorder), and PDR-1 (1981, digital event recorder with gain ranging). The accelerograph product line produced by Kinemetrics, Inc., Pasadena, California, is used in this paper to illustrate strong motion accelerograph features and applications.

SMA-1 Strong Motion Accelerograph

The SMA-1 is a compact, self-contained accelerograph which records L, V and T sensor data on 70mm photographic film. Originally developed in 1969, the SMA-1 has become the "most used" SMA with over 5,000 units installed worldwide. Although both analog and digital tape and solid state recording methods have come to accelerography, the SMA-1 continues to be the clear choice for many

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applications due to its low cost, high reliabililty, simple operation, and straightforward maintenance/repair procedures. The optical system and high contrast black and white photo film produce excellent quality permanent records. Recording capacity is 30 minutes. For detailed record interpretation, the traces are digitized for computer reduction and analysis. The digitization can be done manually, a relatively slow process in which digital coordinates are established by aligning cursor cross hairs on the trace, or with a digitizing table, a faster and more accurate process in which coordinate values are determined by the cursor cross hair position on the table, or with an automatic, computer controlled scanner. Modern digitizing systems provide resolution greater than the trace width. The trace center can be defined so as to produce better than 60 dB dynamic range. Typical SMA-1 applications include regional seismicity networks and soil/foundation/building response studies.

SMA-2 Analog Strong Motion Accelerograph

The SMA-2 is similar to the SMA-1 except that the sensors produce a voltage proportional to acceleration, the recording is done on an analog cassette tape, the recording time is 25 minutes, and the sensors may be installed optionally remote from the recorder housing. The analog magnetic tape cassette medium permits data to be played back into an analog-to-digital converter, bypassing the optical digitization process required of photographic records. The SMA-2 applications are the same as the SMA-1 except the SMA-2 allows remote (such as downhole) sensors, however the SMA-2 dynamic range is somewhat less than that of the SMA-1.

DSA-1 Digital Strong Motion Acccelerograph

The DSA-1 is an extremely flexible (though expensive relative to the SMA-1) accelerograph originally introduced in 1976. Data are sampled at 200 samples per second (sps), converted from analog voltages to 12 bit digital samples and recorded on a digital cassette. At 200 sps the minimum recording capacity is 23 minutes. The 200 sps rate enables accurate representation of frequencies up to about 35Hz (one sixth of 200 sps) (Ref.3) and the 12 bit word (11 bits plus sign) allows a dynamic range of 2048:1 (2 raised to the eleventh power). Data are recorded using a four-track head (3 acceleration channels and 1 parity channel). System noise is held to less than the least significant bit. The digital electronics are contained on three, easily replaced, printed circuit boards. One or two additional boards, each containing 2.56 seconds of Pre-Event Memory (PEM), may be installed in the card cage. When the first PEM board is inserted, power is supplied continuously to the force-balance accelerometers (FBA), and the transduced motion is entered into the PEM. When an event causes the trigger to actuate the DSA-1, the 3-channel data for the immediately previous 2.56 seconds are transferred to tape. Subsequent data enter the PEM and then are recorded on the cassette. Although the use of the PEM greatly increases power consumption (in other SMA's and in the DSA without PEM, power is supplied to the sensors only when the trigger actuates), the record of the P-wave arrival is important for source mechanism and wave propagation studies. And of course the S minus P interval may be used to determine epicentral distance. The DSA encodes the instrument serial number and 2 pps time mark along with the acceleration data of the L and V sensors. If the optional time code generator or radio time receiver are included, this code is added to the T data track. For playback, a strip chart may be obtained with the DSP-1 Digital Playback Unit, or data may be entered directly into a mini computer by the DSP-3 Playback System.

PDR-1 DigiSeis™ Digital Event Recorder

The PDR-1 DigiSeis™ is a three channel digital event recorder for recording earthquake data. The analog input section includes low pass input filters for each channel, with separately selectable cut-off frequencies. Also included is separate automatic gain ranging for each channel, both up and down during an event, allowing a system dynamic range of over 100 dB. The phase encoded digital data are recorded at a density of 1280 bpi. The recording capacities are 45 and 22 minutes, corresponding to user-selectable sampling rates of 100 sps and 200 sps; pertinent data are recorded with the three channels of signal data, including the time of the event (day, hour, minute, second), the instrument serial number, the amplifier gain (1, 4, 16, or 64), the sampling rate (100 sps or 200 sps), and the event number. For playback, a strip chart record may be obtained with the DSP-1, or data may be input to a digital computer through the DSP-3. A switch on these units permits them to be compatible with both the DSP-1 format and the PDR-1 format.

CRA-1 Central Recording Acccelerograph

The CRA-1 utilizes 7-inch wide photo film and galvanometers to record data from external accelerometers. Technically, up to 25 galvanometers can be mounted; however, for adequate trace separation, a maximum of 13 channels is recommended. Recording capacity is 25 minutes. Used extensively on buildings and bridges, the CRA-1 allows a large number of channels to be placed on the same record enhancing the data analysis of relative, phased response at each sensor location. Interpretation of the data is the same as for the SMA-1.

SMA-3 Analog Acceleration System

This central recording SMA is an adaptation of the SMA-2 analog magnetic tape cassette system in which the recorders and control circuitry are centrally located (rack mounted usually) and the accelerometers and trigger are remote. One cassette recorder is used for every three remote acceleration channels, and one control panel can support up to 27 acceleromenter channels (9 recorders). The convenience of central recording makes the SMA-3 useful for dams (Ref.4,10), offshore platforms and for nuclear power plants (Ref.5) where access to the sensor locations is difficult or impossible at times. The SMA-3 system is installed at 50 nuclear plants and several offshore platforms. As with the SMA-2, data are played back with the SMP-1 Playback Unit and may be digitized with an A to D converter.

DSA-3 Digital Acceleration System

The DSA-3 is a central recording SMA based on DSA-1 components exactly as the SMA-3 is based on the SMA-2. High dynamic range, ultra low noise and the optional PEM are all available on the DSA-3.

Figure 1 describes the primary features of each of the described accelerographs.

APPLICATIONS AND ACCELEROGRAPH ALTERNATIVES

The SMA is the major tool of the civil engineer to obtain seismic response data for comparison to those predicted by structural design models; of geotechnical engineers to obtain the relative seismic responses of the soil and the foundation; of building code authors to understand the relative response of adjacent land areas (regional seismicity) and the effect of local geology and topography; and of seismologists to obtain ground motion records for studies of wave propagation, and fault mechanism. Several different accelerographs and options have been developed for these diverse objectives.

The Regional Seismicity Application

A network of SMA's, located at ground level and dispersed in an orderly manner, will provide data on the relative response of each SMA site to a local earthquake. The net is configured so that several adjacent SMA's will trigger from a nearby event. Sites are chosen so that the relative response of different subsurface conditions and different epicentral instances will be recorded and so that the number of potential records is maximized. The configuration can be optimized by statistical computer analysis using such factors as seismicity; geo-tectonic, industrial and population density; and local sub--surface conditions (Ref.6)

The SMA choice for regional seismicity applications narrows quickly to the SMA-1, DSA-1 and PDR-1 instruments. These are designed for installation in remote, rugged areas and the SMA-1 and DSA-1 cast housings require little additional protection. The advantages of the SMA-1 for this application are low cost (one-half the DSA-1 cost), highest reliability (over 5000 installed over a 12-year period and with excellent field results) and simple operating principles. By nature, the study of regional seismicity requires a relatively large number of instrument locations, and of course the probability of obtaining multiple accelerograph records increases as the instrument density increases. Since the primary objective is to describe accurately the relative amplitudes, frequencies and duration of different sites to the same event, and since ultra-low noise, expanded dynamic range and capture of the P-wave arrival are not important for this application, the SMA-1 is the clear choice. The specific configuration recommended is 1g full-scale sensitivity, 0.01g trigger set-point, and TCG-1A Time Code Generator. The TCG-1A Time Code Generator is recommended so that each event will be identified for correlation between several SMA-1's.

Aftershocks (if they occur) can be recorded by taking SMA's to the epicentral region. Several agencies responsible for SMA networks keep a few SMA's on the shelf for this purpose. It is possible of course to relocate some of the network units; however, the removal, transportation and reinstallation takes several hours, or more, during the period when valuable data may be lost. If it can be afforded, a few SMA's, 1g full-scale, should be kept, on charge, ready for quick installation following a major event. It is risky to use 0.5g or 0.25g sensors since accelerations close to the epicenter often exceed 0.5g.

Figure 1
Accelerograph Features

Accelerograph	Configuration Type	No. Channels	Sensor Type	Frequency Response	Full-Scale (g)	Trigger Type	Recorder Type	System Dynamic Range#		Recording Time	Relative Cost	Options
								Ratio	dB			
SMA-1	Self-Contained	3 (L,V,T)	Optical-Mechanical (internal)	0.1-25 Hz	2.0 1.0 0.5 0.25	Vert EM std Pendulum opt OE	Photo film (70 mm)	1024:1	60	25 min.	1.0 x SMA-1	TCG WWVB S/N EO (SMA-1A only)
SMA-2	Self-contained or Central Recording	3 (L,V,T)	Force-Balance (internal) OE	0-50 Hz	2.0 1.0 0.5 0.25	Vert EM std *Pendulum opt* OE	Analog *Cassette*	200:1	46	30 min.	1.8 x *SMA-1*	External *Sensors*
DSA-1	Self-contained or Central Recording	3 (L,V,T)	Force-Balance (internal) OE	0-50 Hz	2.0 1.0 0.5 0.25 0.10	Vert EM std Pendulum Optional OE	Digital Cassette	2048:1	66	20 min. at 200 sps	1.7 x SMA-1	Ext. sensors PEM TCG WWVB 100 or 50 sps
CRA-1	Central Recording	Up to 13	Force-Balance (external)	0-50 Hz	2.0 1.0 0.5 0.25 0.10	Vert EM std OE	Photo film (178 mm)	1024:1	60	25 min.	1.0 x CRA-1	TCG WWVB
SMA-3	Central Recording	Up to 27 per Control Panel	Force Balance (external)	0-50 Hz	2.0 1.0 0.5 0.25 0.10	Triaxial External	Analog Cassette	200:1	46	30 min.	1.1 x CRA-1	TCG WWVB
DSA-3	Central Recording	Up to 12 per Control Panel	Force Balance (external)	0-50 Hz	2.0 1.0 0.5 0.25 0.10	Triaxial External	Digital Cassette	2048:1	66	20 min. at 200 sps	1.3 x CRA-1	PEM TCG WWVB 100 or 50 sps
PDR-1	Central Recording (Portable)	3	Force Balance (external)	0-50 Hz	2.0 1.0 0.5 0.25 0.10	Ratio or difference of STA and LTA	Digital Cassette	2048:1* 64:1** Total	66 36 102	22.5 min. at 200 sps	2.5 x SMA-1	Extra PEM WWVB TCG-1A

#Based on comparison of a full-scale reading to the system noise or resolution

Legend
EM Electromechanical
TCG Time Code Generator
WWVB WWVB Internal Receiver (or DCF-77)
S/N Serial Number Encoder
EO Electrical Output
* From 12-bit A/D
** From 2-bit gain ranging
PEM Pre-Event Memory
L,V,T Longitudinal, Vertical, Transverse
OE Optional External

The Dense Strong Motion Array Application

Dense arrays using multiple SMA's may be used to study the source and effects of large earthquakes. There are three interrelated areas for which the presently available data base is inadequate:

- Source Mechanism - the method by which the fault ruptures
- Wave Propagation - the way that the energy travels from the source to a local area
- Local Effects - the local site characteristics which affect the arriving seismic waves.

The May, 1978 International Workshop on Strong Motion Instrument Arrays considered these applications and prepared recommendations for the size and configuration of each (Ref.7). Source mechanism arrays are used to determine fault rupture characteristics such as rupture propagation velocity, variation of acceleration as a function of azimuth and variation of ground motion intensity. Wave propagation studies, in which the radiation characteristics are evaluated, may be accomplished using the same instrument array as for source mechanism studies. Two types of arrays were proposed by the Workshop: a permanent array to be installed where magnitude 7 to 8 events could be expected and a mobile array for aftershock monitoring or for deployment in the area where a large event is predicted. The DSA-1 or PDR-1 digital SMA's are recommended for strike-slip, subduction and dip-slip faults because expanded dynamic range, pre-event memory and low noise are important factors. The objective of the mobile array would be to record large aftershocks following magnitude 7 or 8 earthquakes. Also a mobile array could be installed in an area for which a near term prediction has been made. Local effects arrays would provide engineering information about the way that radiated waves are modified by local geologic and topographic conditions. The objectives of such an array as suggested by the Workshop are to determine horizontal and vertical gradients of strong motion across a site, soil structural interaction (to test theories of compliance of the soil beneath a structure and the smoothing out of free-field motion by a rigid foundation) and failure of soil masses (such as liquefaction, settlement, compaction, slope failures and surface ruptures).

The Structural Response Application

The feedback of full-scale, high strain level structural response data into the design cycle is extremely important and, at the same time, a frustratingly slow process. Yet it is the most reliable method available to obtain accurate response data. Shorter paths, each with inherent problems, are model testing on shake tables and full-scale testing using ambient excitation. The steps in the cycle are:

- Design
- Mathematical modeling/analysis
- Construction
- Installation of instrumentation
- Recording structural response during an earthquake

- Comparison of actual response to that predicted by the mathematical model
- Modification of modeling and analysis procedures so that actual response can be predicted more accurately

Of course it is not mandatory that every structure in a seismically active area be instrumented. What is important is that structures representative of all types, heights, soil conditions and local topography be instrumented along with special structures and those using new design concepts. Several governmental jurisdictions have either passed local laws or have accepted building code provisions which call for instrumentation of new, tall buildings in seismically active zones. Examples are the legislation passed by several cities in California which accepted Appendix 2314L of the Uniform Building Code, and the State of California law which established the State Strong Motion Program. Administered by the Division of Mines and Geology , this law calls for contribution to a state fund by constructors of new buildings in communities which have not accepted the UBC Appendix 2314L. The Division purchases instruments with the proceeds and places them in structures throughout the state.

Both the SMA-1 (self-contained, triaxial) accelerograph and the CRA-1 (central recording, multi-channel) accelerograph are used in high rise buildings. The SMA-1 is preferred when local ordinances call for three accelerographs to be located at the top, bottom and middle parts of the building because it is the least expensive way to satisfy the requirements. The CRA-1 is used when it is desirable to record the response of several different levels and/or the torsional response (by placing horizontal accelerometers at opposite corners). Up to 13 channels of data can be recorded with 12mm intertrace spacing on the 7-inch wide film. The extra cost of digital recording SMA's is not justified because ultra-low noise, expanded dynamic range, pre-event memory and quick conversion to a computer-compatible tape are not needed.

For bridges, dams and offshore platforms, central recording SMA's are used frequently because, remote, often inaccessible sensor locations are needed. Examples of remote sensor sites are on bridge towers, underneath bridge decks, at dam foundations and abutments (Ref.10) at the mud line beneath an offshore platform and on the ocean floor adjacent to a platform. Thus the CRA-1 and SMA-3 accelerographs are preferred for this type of application. The recorder should be in a clean, dry, accessible room or enclosure.

Impoundment of numerous large reservoirs has induced seismic activity, often where none has been recorded in historical times. It is thought this phenomenon may be due to the reservoir weight, lubrication of fault zones, or both. It is useful to record the microseismic activity before, during and after the construction using sensitive, seismological instrumentation such as the PDR-1 (see Kinemetrics Application Note No.16, "Dam Seismic Instrumentation at Stiegler's Gorge"). The PDR-1 can record both the low level microseismic events and the strong motion events which previously required two different types of instruments.

Commercial nuclear power plants are a special application of SMA's since data must be displayed immediately following an event for use by the plant operators. Several countries, including the U.S., West Germany and England, have regulatory requirements for accelerographs, seismic switches, peak accelerographs, and response spectrum recorders (Ref.8). The central recording SMA-3, with remote triaxial (FBA-3) accelerometers located on the containment foundation, reactor building, free-field and turbine building, has been installed at more than 50 plants, worldwide. The DSA-3 digital system dynamic range, low noise and other advantages are not needed for an engineering application. The nuclear plant instrumentation system is described, along with a discussion of regulatory requirements, in Kinemetrics' "Nuclear Power Plant Seismic Instrumentation Manual"(Ref.9).

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