1.3 - RELIABILITY OF RECORDS

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SYNOPSIS

The reliability and accuracy of information derived from strong-motion accelerographs are considered from the point of view of: (a) influence of site and installation on the measured quantities and their interpretation; (b) maintenance problems; (c) accuracy and reliability of the basic transducer-recorder system; and (d) influence of data processing on information retrieval. Some speculations about future developments are offered, and the basic principles involved in instrumentation systems designed for the special needs of earthquake engineering are reviewed.

INTRODUCTION

The present discussion will be limited to records obtained from networks of time-recording strong-motion accelerographs, since this is by far the most important source of instrumental data for earthquake engineering. There are now some 4000 accelerographs of the mechanical-optical type distributed throughout the world from which several thousand records have been obtained. This is a large enough sample so that realistic evaluations of the field reliability of the instruments and of the adequacy of the data processing techniques can be made. Emphasis will be placed here on the things that can go wrong, so it should be made clear at the outset that the present overall level of reliability and accuracy which is being attained in practice is in many respects satisfactory. As the number of instruments in the world increases, however, it will be more difficult to maintain the present level of performance. It should also be understood that the performance characteristics and field reliability of some of the more elaborate instrumentation systems involving central recording of multiple transducers of different types now being installed in a number of dams, bridges, and buildings can not as yet be realistically assessed, and may present new problems for the future.

INFLUENCE OF SITE AND INSTALLATION ON RECORDS

A fundamental point is the extent to which the measured acceleration of the instrument case is representative of the site for a particular purpose. Assuming that the accelerograph is firmly fastened to a foundation whose dimensions and mass are such that no appreciable pier response is introduced over the frequency range of interest, questions remain as to whether a soil-structure interaction might influence the result or whether a particular soil, sub-soil, or local geological condition might have special characteristics that should enter an interpretation of the result. This is of direct concern for the large number of accelerographs which are located in the basements of buildings. Such building influences can be studied by comparing basement acceleration records taken in nearby buildings. In Table I such a comparison is

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made for six buildings located within a few hundred meters of each other (4). The buildings are of widely varying height, configuration, and structural and foundation type. The first five are located on the same sedimentary rock formation overlain by thin soil layers; the sixth site is on a deeper alluvium. Since peak accelerations, velocitites, and displacements effectively sample different portions of the frequency spectrum, a comparison of the three peak values gives a rough overall idea of the degree of similarity of the sites. Whether the values shown in the table will be considered to be very similar or to display significant differences, will depend upon the use to which the data are to be put. Considering the accuracy with which the data processing can be carried out, and the extent to which true free-field measurements could vary over short distances because of many source mechanism and transmission path effects, I would conclude that for many purposes the basement records of Table I could be taken as representative of free-field site motions.

If the dimensions of a relatively rigid structure approach the wavelength of seismic waves, spectra derived from measurements made within the structure will be modified to some extent. This has been experimentally studied for a site in Los Angeles for which simultaneous measurements were available within a building and at a free-field site close to the structure (3, 5). The results have been as expected, with a small modification of the spectral peaks at the relatively high frequencies corresponding to waves of a length similar to the horizontal building dimensions. Another aspect of this same situation is that all points on the base of a long structure such as a dam cannot be expected to have the same motions over the whole frequency range, and the piers of a long bridge may have relative foundation motions of significance.

Examples come to mind of special foundation conditions which have had significant influence on the measurements made in buildings. In Mexico City measurements were made during earthquakes in 1962 in the basement of a 43-story building and at an adjacent site in a small structure in an open park which could be considered as a free-field station (16). Predominant periods appeared in the park site spectra which could be satisfactorily explained on the basis of a simple mathematical model for motion of the underlying soft clay layer. Measurements made in the basement of the building gave spectra similar in many respects to the adjacent park site. In this case the building measurements could have been used as a good estimate of free-field motion even in the presence of unusual soil conditions which strongly influenced the ground motions. Somewhat similar comparisons for small amplitude ground motions have been made at the Southern Pacific Building in San Francisco which is founded on a relatively soft filled ground. The motions recorded there were very similar in the building basement and in a vacant lot about 150 m distant (2). These measurements can in turn be compared with spectra calculated from measurements made in the building basement during the 1957 San Francisco earthquake, which indicated a pronounced peak in response corresponding to the measured fundamental period of the building (6). The detailed nature of the soil-structure interactions cannot be completely elucidated by the above experiments since the buildings are present for all tests and could influence ground site motions as well as be influenced by them. Additional investigations of such soil-structure interactions are needed, but it cannot be expected that the necessary basic data will accumulate very rapidly.

Little information is at hand on the local soil and geological conditions at most of the strong motion accelerograph sites. While these basic data are of course essential for the ultimate interpretation of the records, it is probably not necessary to carry out extensive investigations prior to the earthquake. Many stations may never record an important accelerogram over their whole life, and in any event the soil and local geology are not usually so disturbed by the earthquake that studies after the event would be seriously defective. For every accelerogram of engineering interest, it is to be hoped that more complete information on local site conditions will become available.

Very simple problems of location and instrument orientation may sometimes prove troublesome. For example, since publication of the original data reports on the San Fernando earthquake, the Post Office addresses of several buildings have been changed, causing some confusion as to identification of sites. A notable example of orientation error is the Pacoima Dam record, which in the original reports was given an orientation which was subsequently discovered to be about 30° off, apparently because of an incorrect application of a magnetic declination correction to a compass reading. Some 90° orientation errors have resulted from complicated stairway and basement hall configurations.

MAINTENANCE PROBLEMS

Experience in the United States goes back to 1933 when the first accelerograms were obtained from the Long Beach earthquake. A peak of maintenance efficiency was reached in 1968 with the Borrego Mountain earthquake, when 114 accelerograms were obtained with only one operating failure (8). From 1968 to 1971 the number of installed accelerographs in the U.S. increased by a factor of two, from 225 to 550, while the size of the maintenance staff remained essentially constant. This reduced service capability was reflected in the results from the 1971 San Fernando earthquake during which 229 records were obtained from 272 triggered instruments, giving a 16% loss ratio. Of the 43 lost records about 70% were the consequence of battery failures (9). Other difficulties included six film transport defects and three relay failures. Since that time numerous improvements have been made in instrument design and in field installation and servicing procedures which should improve this reliability record. A balance must be achieved between service costs and network reliability which will depend upon such factors as site preparation, labor costs, and complexity of instrumentation, which may differ widely in various parts of the world (7, 12).

Present estimates for the U.S. network are presented in a very approximate way in Fig. 1 (10). The width of the regions shown there indicates the nature of the uncertainties involved, which permit only rough trends to be discussed. The zero service time ordinate indicates that some of the instruments must be expected to be defective in some way immediately after installation. With a four-months service period, about 95% of the accelerographs should obtain usable records, although perhaps only 60% of the records would be expected to be perfect in all respects. The lower boundary is probably the place where improvements are most likely to be made. One problem which often presents itself is the incomplete record, which although defective may tempt one to an inaccurate data processing. Such difficulties as missing time marks or traces, erratic or slipping film transport, improper optical trace adjustment resulting in missing portions of the record, and late starts because of trigger malfunctions are of this character.

ACCELEROGRAPH ACCURACY

Mechanical-optical accelerographs provide a fortunate combination of ruggedness, simplicity, high signal-to-noise ratio, and wide frequency response. A properly adjusted optical trace on a correctly processed 70-mm film will easily resolve a low-amplitude 30 Hz signal, and can be read to an accuracy of one part in a thousand at a typical full-scale 1 g reading. A dynamic range of 1000 to 1, or 60 db, is thus realized. Some recent results with well-adjusted optical instruments have indicated that an even better resolution has been obtained under field conditions (1). With modern data processing techniques, a frequency range of from 25 Hz on the high end to some 15 seconds period at the low end is readily achieved (13). As now designed, inaccuracies caused by such factors as cross-axis sensitivity and misalignment have been kept at a minor level for most applications, and can be corrected for in more exacting investigations (15). The accuracy of internal timing systems is better than 0.2%, and such basic instrument parameters as sensitivity can be checked to the order of 0.5%. These overall characteristics are compatible with most of the intended uses of the data, and major improvements are not likely to be cost-effective, particularly if they involve increased complexity and reduced field reliability. The present type of self-contained three-component accelerograph as used in multiple installations depends upon redundancy for increased system reliability. Three separate independent accelerographs, each with its own starter, film transport, and timing system, have been considered to have an overall reliability advantage for structural instrumentation over a central-recording type system. For example, had there been no redundant starters in Los Angeles buildings during the San Fernando earthquake, an additional 14 records would have been lost (9).

DATA PROCESSING

The process of extracting the maximum amount of information from an accelerogram requires a broad view of the whole instrumentation including all of the factors mentioned above, as well as additional considerations of record digitization, correction procedures, and computational techniques. An estimate of the cost of accelerograms makes it evident that a considerable effort in data processing is highly justified The U.S. network has produced since 1933 about 350 good accelerograms of sufficient size to be of engineering interest. Considering the cost of acquiring, installing, and maintaining this network, the average cost of each accelerogram is well over $10,000.

The most difficult step in the data processing has been the digitization of the analog photographic trace to produce computer-compatible punched card or magnetic tape data. Systems now under development should make it feasible to do this digitization on an almost completely automatic basis, and this is perhaps the most important development to be hoped for in the whole instrumentation system. A very important element in the evolution of data processing for accelerograms has been the modern development of digital filtering techniques, as this has made it possible to carry out transducer and baseline corrections to a high accuracy over a much wider frequency range than had hitherto been feasible (13). It should be noted that the special requirements of the strong-motion earthquake measurement - that the instrument be very close to a future earthquake source of unknown location and time - dictates a network involving a relatively large number of field instruments. This suggests a system which places the maximum simplicity in the field, with complicated data processing equipment and computers remaining in the laboratory. The present day combination of the relatively simple mechanical-optical accelerograph in the field, with the digitizer and computer system in the laboratory, comes close to this ideal.

When using the output of any standard processing system which has been designed to produce large amounts of data on a routine basis, it should be appreciated that many compromises have probably been made which could reduce the information content for particular records. The processing of U.S. earthquakes by the standard program developed by the California Institute of Technology, for example, uses just two basic filter intervals for all records, although it is evident that an individually designed optimum filter for each record would significantly improve certain of the accelerograms for some purposes. As a second example, the problem of initial motion estimates may be mentioned. Standard processing systems often employ some type of least squares base line fitting which in effect produces an estimate for the small unknown initial movements which may have occurred before the triggered accelerograph attained full operating condition. For some records, such estimates could become so large as to significantly influence calculated response spectra.

Research investigations should start from the original unprocessed accelerogram, using techniques tailored to the particular record and to the object of the study. To encourage this approach, the Caltech program produces as the first stage in the output the "uncorrected" digitized accelerograms which are as close a representation of the original accelerogram as can be achieved by a digital process.

The capabilities of any measurement system can be measured by certain noise characteristics which limit the ability of the system to produce low-level analyzable records. As an example of the current state of the art in this respect, the basic noise properties of a standard U.S. SMA-1 accelerograph and its associated data processing system are shown in Fig. 2, compared with estimates of earthquake spectrum levels (14). It is clear that beyond a certain distance, for example, earthquake ground motions will have become so small that the instrumentation system cannot be expected to accurately recover them. Some of the records included in the Caltech standard uniformly processed data reports are of a low level not far above the noise, and should be used with caution over some parts of the frequency spectrum.

THE NEXT GENERATION OF INSTRUMENTS

Proposals are already at hand for new types of accelerograph systems taking advantage of recent remarkable advances in solid state electronic digital technology. Since the digitization of analog film records has been cited above as one of the major steps in data processing, an attractive idea is to carry out this digitization electronically within the instrument itself, and to record in digital form on magnetic tape. Solid state integrated circuit electronics makes it possible to do the digitizing in a very small space within the field accelerograph, and the digital tape format avoids most of the basic noise problems of analog magnetic tape. The use of the digital format makes it relatively easy to provide the instrument with a short memory so that the onset of ground motion is recorded. Although this memory capability is not as important now as before the development of reliable vertical triggers, it is a desirable feature if it does not seriously compromise system cost and reliability. A part of the price for the above desirable features is a significantly higher power consumption which reduces the unattended life of the equipment to several hours compared with several months for current mechanical-optical accelerographs. This could result in the loss of important aftershocks of a major earthquake. The main problems of the presently available digital systems are associated with the analog transducer and the magnetic tape transport. Solid state memory devices are now under development which could eliminate the tape drive, but so far no practicable ideas have emerged for a direct digital transducer.

Specifications have recently been drawn up for a digital accelerograph based on current technology and the recommendation has been made that it be introduced as the next generation of standard instrument for the U.S. strong-motion network (11). The main features of this proposed system are: (a) analog force-balance servo type transducer having a natural frequency ≥ 40 Hz and a full-scale output of from 2 to 10 volts; (b) acceleration type trigger, flat from 0.1 to 15 Hz, with threshold adjustable from 0.005 g to 0.05 g horizontal and vertical, and a 0.1 sec delay time for full operation; (c) digital magnetic tape recording, resolution 12 bits (1 in 4096 for ± full scale), 100 samples per sec, 5000 bits per sec, 1.5 to 2 sec memory, 15 minute recording time, and a minimum operating time without external power of 6 hours. Overall system frequency response is specified as 0.05 to 25 Hz. In addition, the specifications call for a cassette-type tape suitably coded to permit complete playback capabilities and processing for digital computer input, as well as the provision of convenient means for system calibration and checkout.

The major uncertainties to be anticipated in network applications of equipment of this type are: (a) long-term reliability in the field; (b) design of suitable field test and calibration devices for adjusting and checking out the system; (c) the level of competence and training required of field technicians and data processors; and (d) economic and manufacturing cost factors associated with market size and development expenses. The only way to answer such questions is to proceed with instrumental development and network installation as expeditiously as possible, carrying out at all stages realistic comparisons with existing devices.

Feelings as to the desirability of the immediate development of digital systems depend a good deal on one's estimate of the importance of rapid digitization of accelerograms. Although problems involved in the digitization of analog photographic traces are troublesome, their importance for the whole instrumentation system is sometimes exaggerated. In my opinion, digitization requirements do not represent a decisive disadvantage for the film-recording systems for the following reasons: (a) A large amount of information of immediate practical importance is quickly available on the analog record without digitizing or further processing. Practical decisions which must be made promptly after an earthquake, such as the need to evacuate a damaged structure, or to empty a reservoir, can be made from the analog record and are not likely to be significantly modified by additional data processing. In fact, the analog film record has many advantages over a digital tape for this purpose, since it can be developed with facilities readily available in any small town, and the significant features can be quickly determined by persons with a minimum amount of training or experience. (b) Even though a large earthquake should occur near a dense accelerograph network, it is not likely that there will be more than a few dozen key records requiring immediate attention. In the San Fernando, California, earthquake, for example, although there were a total of 241 records, and almost all of them proved to be of some ultimate interest, there were only a half dozen or so near the epicenter of such special value that rapid processing was of great importance. (c) No matter what future developments take place in digital systems, the large number of analog film accelerographs now existing in the world will present for many years the need for some kind of film digitizing capability as mentioned above. Several automatic scanning type digitizers already exist, and improved models are under development, which should remove most of the pain from the analog film digitization process.

SOME BASIC PRINCIPLES

In conclusion, a few basic ideas which should be kept in mind when developing or altering any strong-motion earthquake data acquisition system will be emphasized. (1) From the very beginning of transducer and network design, it is a good idea to consider the ultimate use to which the data are to be put. An instructive exercise to begin instrument design is to imagine that everything worked perfectly, and then to contemplate what is to be done with the results. (2) The type of instrument and data processing system is usually a minor part of the problem. Care in field installation and servicing, repeated calibration and checking of both field and laboratory equipment, and evaluation of the accuracy and reliability of all steps in the data processing chain are the real keys to success. (3) The whole system must be thought of as an entity: field accelerographs, calibration, photographic enlargement, digitizing, computations, must all be evaluated as integral parts of a whole. Care must be taken not to change one part of the system without a study of the implications for the whole system. For example, introduction of a magnetic tape recording accelerograph would require a reconsideration of the whole data processing chain, and a reevaluation of correction and computational techniques. (4) It cannot be assumed that a newer technology is necessarily an improvement for a particular application. Although we now have laser beam interferometers, we still use meter sticks for some displacement measurements. A completely digital accelerograph, for example, has many desirable features for the problems we are considering, but as outlined above, there are also some critical defects to be overcome.

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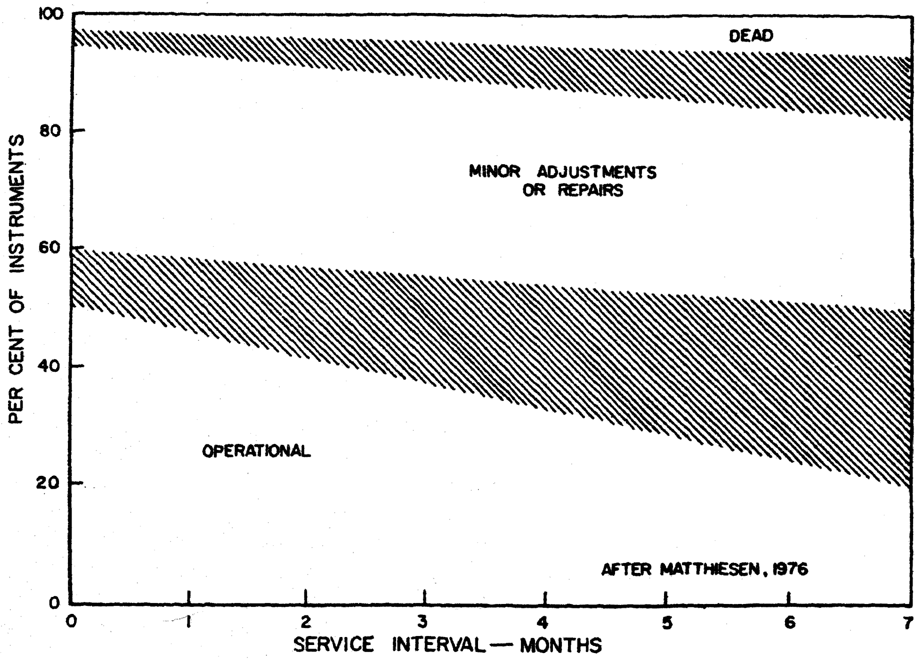

FIG. 1 FIELD RELIABILITY OF STRONG MOTION ACCELEROGRAPHS
U.S. NETWORK 1933-1975

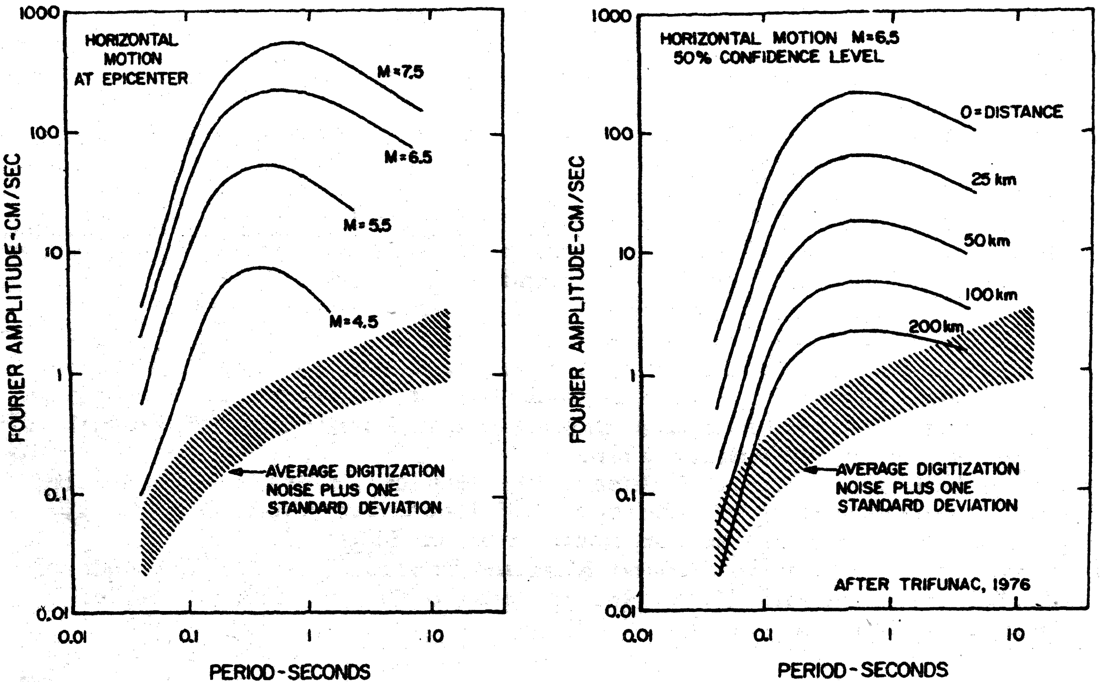

FIG. 2 NOISE CHARACTERISTICS OF STANDARD ACCELEROGRAPH SYSTEM

TABLE I

PEAK GROUND MOTIONS FROM ADJACENT SITES
SAN FERNANDO EARTHQUAKE - FEB. 9, 1971
(AFTER REF. 3, 4)

SITE	DISTANCE FROM SITE 1 (m)	STORIES	TYPE	ACCELERATION (g's)		VELOCITY (cm/sec)		DISPLACEMENT (cm)	
				NS	EW	NS	EW	NS	EW
1	0	31	SF	0.11	0.13	18	18	9	13
2	140	17	RC	0.12	0.12	16	18	7	11
3	210	12	RC	0.12	0.10	15	16	10	9
4	240	11	RC	0.14	0.12	22	19	11	12
5	300	7	SF & RC	0.17	0.18	18	17	9	10
6	350	21	SF	0.17	0.14	17	21	8	12

SF = steel frame; RC = reinforced concrete

DISCUSSIONS

P.C. Saxena (India)

Considering that a very high signal to noise ratio is attainable with modern data loggers and mini-computer or micro-processor based data acquisition systems I do not quite understand how Professor Hudson regards the photographic type of recording instruments to have better signal to noise ratio than the modern digital instruments.

A.N. Tandon (India)

While a good number of studies of earthquake records recorded by different types of seismographs installed on different geological foundations are available, I would like to know if similar studies have been made with accelerographs. This is important because the net work of world accelerograph stations consists of a variety of instruments.

W.O. Keightley (India.)

Although individual strong motion records might be rather reliable indicators of what takes place at given points, the scant spatial distribution of instruments in an epicentral zone might be looked on as a lack of reliability in recording all the significant aspects of the phenomenon of a damaging earthquake motion. In some instances factors of approximately 2.0 in intensity have been recorded at two points only hundreds of feet apart. Is it not possible that there are factors of 4.0 in the vacent spaces between instruments ? Can you make any recommendations for instrument development and placement to address this problem of lack of information ?

P.N. Agrawal (India)

The problem of maintenance of the strong ground motion recording instruments has been very rightly highlighted by Prof. Hudson in his paper. In India by very carefully maintaining a small number of only the simple devices (Multiple Structural Response Recorders) we have been able to obtain reliable data (though approximate in nature) due to the basic character of the devices itself.

In my opinion the easy and direct test of the reliability of strong ground motion records should be through the direct measurement of the response of structures for which instrumentation should be developed now.

A.R. Chandrasekaran (India)

Though it is always desirable that records obtained of any event should be very reliable, what is more important in strong earthquake motion measurements is the instruments give a record. In a country like India where instruments have to be located in remote undeveloped areas, the instrumentation has to be simple and minimum maintenance should be capable of being carried out locally. However, the instruments should be calibrated immediately after an event by trained personnel and the calibration results along with other inspection notes should be available along with the record for proper evaluation. In view of the fact that the earthquake phenomenon is random in nature, very high precision in recording is not necessary but since the event is rare, it should not be missed.

Author's Closure

The comments made by the discussors significantly assist in a clarification of a number of important practical points. Saxena properly emphasizes that very high signal to noise ratios are readily attainable with modern digital data systems. The critical questions about such digital systems are involved rather with cost, complexity, and power requirements. Comparing the characteristics of current standard photographic accelerographs with digital systems of equivalent signal to noise capabilities, it appears that presently available digital systems are more expensive by a factor of two or three, and that they require significantly more standby power, thus limiting their no-power operating life. These deficiencies may of course be overcome within a few years by rapid technological developments in the digital field. The key advantage of the digital systems - their ability to rapidly handle large quantities of data - has not so far been a critical limitation of the optical-photographic system in view of the fact that relatively small numbers of strong motion records are likely to be obtained for some years to come.

The point made by Tandon concerning measurements made on different types of instruments is likely to become more important as new equipment is developed and introduced. In the early days of strong motion instrumentation, only a few accelerograph types were in use, and detailed comparative tests had been made on all of them. As new instruments appear, it will be important to make critical evaluations of their characteristics, and careful comparisons with existing network equipment. This is especially important in view of the practical impossibility of replacing many of the existing instruments with newer devices.

Agrawal and Chandrasekaran emphasize various elements of the instrument maintenance problem, which is no doubt the single most important aspect of the whole reliability question. It is not often appreciated by instrumentation experts in other fields just how profoundly the special requirements of strong earthquake recording must influence all aspects of the instrumentation system.

The important questions raised by Keightley can be fully resolved only by actual measurements with dense networks. Because of the large resources required for such measurements, and of the universal value of the results, this is a subject which would seem to be a natural one for an international cooperative program. Proposals to this end have recently been made, and are being explored through I.A.E.E. sponsorship. At the same time, additional light could be thrown on such distribution problems by increased study of mathematical models aimed at a more realistic representation of various elements in the source to site seismic wave transmission path.

The contributions made by the discussors, and by those participating in the oral discussion at the panel discussion, are much appreciated by the panel organizers. The whole subject of reliability of records is clearly receiving much informed thought, which augers well for the future of our basic measurements program in earthquake engineering.