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STRONG-MOTION EARTHQUAKE MEASUREMENT : PAST ACCOMPLISHMENTS AND FUTURE DIRECTIONS

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SUMMARY

This paper discusses some of the accomplishments of the worldwide effort in strong-motion earthquake measurement since the 1978 Hawaii Workshop and looks at the challenges of the future. The past decade has been one of significant accomplishments in the development and deployment of new instruments and in increased international cooperation. The challenges of the next decade lie primarily in the areas of increased data utilization and an ongoing commitment to the maintenance and expansion of strong-motion installations throughout the seismically active regions of the world. These challenges can be met through the continued efforts of the international strong-motion measurement community.

INTRODUCTION

Earthquakes represent a major threat to some of the most highly populated and some of the most technologically developed regions of the world. In order to deal appropriately with this threat, it is necessary to have knowledge about the nature of the strong ground shaking that results from an earthquake. As this knowledge becomes more refined, more intelligent decisions can be made regarding such matters as land use planning and the design of safe, economical structures. The most effective means for understanding the nature of strong-ground motion is to measure and analyze the motion resulting from an actual earthquake event. Thus, the field of strong-motion earthquake measurement has developed over the years into an important specialty within earthquake engineering and seismology.

In 1978, the International Association for Earthquake Engineering convened an International Workshop on Strong-Motion Earthquake Instrument Arrays in Hawaii. The purpose of this workshop was to promote the development of strong-motion instrumentation worldwide, and to develop specific plans for the deployment of strong-motion arrays. Experts in earthquake engineering and seismology from all over the world participated in the Workshop. The proceedings of the Workshop identified favorable locations for strong-motion installations, presented example designs for various types of arrays, discussed desired instrument specifications, and recommended the creation of an International Strong-Motion Array Council to facilitate the deployment and operation of strong-motion instrument arrays worldwide.

The Hawaii Workshop proved to be a watershed for activity in the field of strong-motion measurement. The decade that followed has been one of unparalled rapid development in instrumentation and expanded deployment of strong-motion instruments. This paper reviews some of the significant accomplishments of the past decade, describes some of the challenges that have resulted, and discusses some of the future needs and directions in strong-motion measurement.

At the outset, it is appropriate to define some important terms which will be referred to frequently throughout this paper. The terms are: array, network, and autonomous station. These terms describe different types of strong-motion instrument deployments. The working definitions used herein are indicated below.

> *Array*—A concentrated deployment of stations arranged in a specific geometric pattern and intended to make measurements that are correlated in both space and time.
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> *Network*—A system of separate but interrelated stations, usually deployed over a fairly large area. The interrelationship may be a consequence of a common tectonic feature, such as a fault, or a common organizational responsibility. A network may contain one or more arrays as subelements.
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> *Autonomous (or stand alone) station*—An instrument deployment (often a single instrument) designed to record data that is not intended to be related directly to data from any other station. An autonomous station may be part of a network in which the stations are interrelated for reasons other than direct correlation of the data.

Arrays may be deployed to measure ground motion, structural response, or both. High accuracy timing is critical in an array due to the need to correlate measurements at different stations. A pre-event memory or common trigger is also highly desirable in order to be able to study the progress of motion across the array. Accurate timing is not as critical for a network or for an autonomous station. However, such deployments may have other requirements such as low power consumption, robustness, reliability, and ease of maintenance.

A DECADE OF SIGNIFICANT PROGRESS

In the decade since the Hawaii Workshop, there has been significant progress in the development of new instrumentation, in the deployment of instruments in arrays and networks, and in increased international cooperation. This progress has resulted in new challenges for the strong-motion measurement community. These areas are discussed below.

New Instruments Over the past twenty or so years, there has been a major revolution in electronic instrumentation with the transition from analog-based to digital-based designs. This revolution has also affected strong-motion earthquake instrumentation. At the time of the Hawaii Workshop, nearly all of the strong-motion instruments were analog in design. There was some use of magnetic recording media in place of traditional optical or mechanical media, but the concepts were still analog. In the ten years that followed, reliable digital instruments were developed and rapidly accepted by the user community. At present, the installation of digital instruments is outnumbering the installation of analog instruments by a factor of about two to one.

Analog instruments like the U.S. manufactured SMA-1 and Japanese manufactured SMAC series are still the most widely deployed instruments. It is estimated that there are presently nearly 8,000 such instruments in operation in various parts of the world. These instruments have established a long record of proven reliability and a high level of user loyalty. Due to their relatively low power consumption, service simplicity, and reliability, they are still the instruments of choice for many autonomous stations, especially those which are not readily accessible. Because of their lower initial cost, they are also often preferred when this factor is a major consideration.

Digital instruments have received the greatest acceptance in array applications, both for ground motion and more recently for structures, where accurate correlation between instruments is essential and the amount of data generated may be expected to be large. Digital instruments offer a number of advantages over their analog counterparts, including: higher resolution, greater dynamic range, more accurate timing, pre-event memories, more flexible triggering algorithms, remote interrogation and command capability, and direct digital playback of recorded data. Of course, the user pays for these advantages with a higher initial capital cost. However, some, if not all, of the capital cost differential may be recovered through reduced data management and maintenance costs, depending on the application.

Early digital instruments recorded the data on magnetic media, which was subsequently read on a special playback device. Newer digital instruments record the data in solid state memories which can be dumped into a variety of conventional digital devices such as a personal computer. Often, the data can be previewed or processed on the spot with a portable personal computer.

The latest digital recorders have a dynamic range of 66–126 db with 12–16 bit resolution and sample rates of 200–1000 sps. The solid state memories can store from 4–6 Mb of data. Most digital, and some analog, instruments now employ force balance accelerometers (FBA) which extend the "flat" range of the transducer from DC to 50 Hz or higher. This has provided the strong-motion measurement community with an extraordinarily powerful set of tools.

New Deployments In 1978, it was estimated that there were approximately 5,000 strong-motion instruments deployed worldwide. In the intervening decade, the number of instruments deployed has more than doubled. New arrays have been installed and networks greatly expanded. Japan, the United States, and Yugoslavia have established programs which implement the recommendations of the Hawaii Workshop by independently setting up strong-motion arrays. International cooperative array projects have also been undertaken, resulting in the SMART-1 array in Taiwan and an array in the aftershock region of the Tangshan earthquake. Strong-motion networks have been significantly expanded in Italy, India, Mexico, and Turkey as well as in Japan, and the U.S.

A variety of different strategies have been employed in the arrays that have been deployed. The surface geometry varies from circular to rectangular to linear. Both surface and down hole instruments have been deployed. The down hole instruments have presented problems in some applications, but the ability to obtain such data has steadily improved. Instruments have even been successfully deployed for extended periods on the ocean floor. Both fixed and mobile arrays have been deployed.

The importance of these new developments cannot be too strongly emphasized and the many individuals responsible for this rapid growth in the deployment of strong-motion instruments deserve a sincere vote of thanks for their efforts.

Increased International Cooperation Following the Hawaii Workshop, the International Association for Earthquake Engineering (IAEE) and the International Association of Seismology and Physics of the Earth's Interior (IASPEI) established the International Strong-Motion Array Council (ISMAC). The purpose of ISMAC is to provide a focal point for international cooperation on strong-motion array (and network) projects. The Council has met regularly since its formation and, though it has no specific long term sources of funding, has attempted to promote greater international interest and cooperation in strong-motion arrays and measurement. It has established committees to develop minimum instrumentation standards, to assist in network and array design, and to explore the possibility of establishing an international mobile array. It has worked successfully to bring about the convening of a series of International Workshops on Strong-Motion Data Processing and is assisting in the organization of a series of International Workshops on the Effects of Surface Geology. It is also participating in the international experiments on the effects of surface geology.

ISMAC has worked diligently to encourage all forms of international cooperation in the area of strong-motion studies and will continue to do so in the future. The existence of a number of successful bi-lateral cooperative strong-motion projects is a testimony to the individual and collective efforts of the members of the Council.

New Challenges The past success of the strong-motion measurement activity has created a new set of challenges. Much new data have been obtained during the past decade, and these data are gradually being used to obtain answers to some of the complex questions facing earthquake engineers and seismologists. It has become apparent, however, that the rapid growth in the deployment of strong-motion instruments and the resulting expansion of the data base have, in some cases, outrun the application of these data. It is a serious challenge to find ways to ensure that the data obtained from strong-motion instruments are put to use in a timely manner, not just by scientists and engineers, but also by those charged with the responsibility for public policy.

Another significant challenge is to insure that adequate resources are available to both maintain existing arrays and networks in a state of readiness until they achieve their objectives, and to upgrade and expand strong-motion installations worldwide. In this regard, it may be necessary to devote resources to substantially improve current systems for data retrieval, processing and dissemination which may not be adequate in the event of the occurrence of a major event in a highly instrumented region.

These challenges provide the backdrop for the next decade in strong-motion studies. They are formidable challenges, but with careful thought and planning, the next decade can be just as successful, and more so, than the past decade.

FUTURE DIRECTIONS

If significant new advances are to be made in the field of strong-motion studies, progress will need to be made in a number of specific areas. Some of these are discussed in detail below.

More Sharply Defined Goals and Objectives As we move into the 1990's, it is likely that there will continue to be intensified fiscal pressures on strong-motion as well as other earthquake related research. It will become increasingly important that new installations of strong-motion instruments be motivated by a clearly stated set of objectives with major milestones and cost estimates including operational as well as capital expenditures. Merely recording more data will not be an adequate justification for the major commitment of resources required for sophisticated new arrays and expanded networks.

Where feasible, it may be appropriate to develop projects with multiple objectives. For example, currently available high dynamic range digital instruments with multiple sensors make it possible to measure both strong and weak ground motion with the same instrument. The weak motion can be used to develop and calibrate theoretical ground motion and structural models in the linear range while waiting for strong-motion data to become available. Such a dual objective would also help to provide a more uniform level of effort, especially for smaller projects. This approach may be desirable from both a funding and training point of view.

Participation in planned international experiments with well defined goals and good management may be a way to help provide a sharper focus for strong-motion programs that lack the internal resources for a high level of planning.

Greater Application of Data There is sometimes a tendency on the part of those who operate strong-motion arrays and networks to be rather possessive with their data. This is understandable, considering the great time and effort spent in gathering these data. Certainly, a researcher should have the opportunity to benefit from the data he has worked to obtain. However, since strong-motion data has great potential benefit to all of society, there is a moral responsibility to make this data available to the largest possible user community in a timely manner.

For this one reason, some feel that strong-motion programs should not be *operated* by researchers. Rather, they feel that individual researchers should be involved only in the establishment of goals and objectives, in the design of the experiment, and in the analysis of the data which is made freely available to all interested parties. Others would argue that more significant analysis of the data is likely to result if the researcher has a personal investment in the gathering of that data.

Regardless of one's position, it is evident that improved means must be found to promote the study of strong motion data worldwide. Archives of strong-motion data are swelling, but often only a small fraction of these data receives careful, systematic scrutiny and analysis. In California, over 850 three or more component records have been obtained by the Division of Mines and Geology Strong-Motion Instrumentation Program from earthquakes during the past two years alone. Recognizing that only a small portion of these data was being studied by the user community, the Program set up a special research grant program to promote the study of significant records. The same problem exists to some extent worldwide. Dealing with this problem will be one of the greatest challenges of the next decade.

One way to increase data utilization is through greater interaction between those conducting strong-motion experiments and those who analyze the data. It appears that the development and verification of geotechnical, structural, risk and socio-economic models has begun to lag behind the available experimental data. This may mean that analysts merely need to focus greater attention on the interpretation and modeling of existing data. Or, it may mean that analysts have concluded that the existing data base is not adequate for their specific purposes. In any case, it is vital that there be greater cooperation between analysts and experimentalists in the area of strong-motion studies.

Expanded International Cooperation Ways must be found to increase international cooperation in strong-motion studies. One country may have high seismicity and an ideal geologic environment but lack sufficient resources for the kind of instrumentation and data analysis that would take full advantage of these conditions. In this case, an international cooperative program may provide the answer. Greater multi-national cooperation needs to be encouraged where possible. A good example of this type of cooperation is the International Experiment on the Effects of Surface Geology, which involves separate activities in at least five different countries with participation from more than seven countries. This type of cooperative activity should be expanded.

One recommendation of the Hawaii Workshop that has never been fully implemented but still deserves serious consideration is the establishment of an international mobile array of strong-motion instruments which would be available for rapid deployment worldwide in the event of a major earthquake. This array was intended to be used to study source mechanism, wave propagation, and local site effects using the aftershocks which would follow a significant main event. Setting up such an array would require a very substantial effort, including establishing protocols for mobilizing into various countries, but the benefits could be considerable.

ISMAC should play an expanded role in promoting international cooperation in strong-motion studies. However, present constraints on its ability to obtain funding through its principle parent organization, IAEE, may limit that role.

Upgraded Instrumentation In the next decade, there will be a continued movement toward greater use of digital instrumentation. This will be due partly to the better specifications of the digital instruments and partly to the simplified data processing required for these instruments. The digitization of analog records now presents a serious potential bottleneck to the timely use of such data in the event of a major earthquake in which a large number of instruments are triggered.

As new digital instruments are incorporated into arrays and networks, operators should insist that these instruments be thoroughly field tested and that the manufacturer provide complete documentation on all system elements including: transducer characteristics, amplifier characteristics, gain ranging hardware or software, anti-aliasing filters, and data compression algorithms if employed.

When an analog instrument is replaced by a digital instrument, it could be relocated to a less “critical” site or transferred to a user whose requirements will be met by such an instrument. A significant worldwide redistribution of used analog instruments could result with these recycled instruments being used to enhance the overall earthquake data gathering capability in regions not now adequately covered. However, the longer term issues of instrument maintenance and data processing must also be addressed. Careful planning is clearly called for by those operating significant arrays and networks to assure that the conversion to digital instrumentation is done in an orderly and cost effective manner.

Another possible future development in instrumentation which needs consideration is real time monitoring, data analysis, and dissemination. Real time earthquake warning systems have been deployed for many years in Japan, and are currently under study in the United States. Although early warning is an obvious possible use of real time data, other potential benefits may actually be more important. For example, real time, on-scale ground motion data can be of great value in emergency response management, or in evaluating the likelihood of aftershocks or of a subsequent main shock. If structural response data were available on a real time basis, it might be possible to make more timely decisions concerning the need to evacuate buildings or other facilities, the urgency and nature of structural repair required, and to further assist in the emergency response process. Real time monitoring of strong-motion data is technologically feasible at the present time. Whether it will become an important element in strong motion measurement remains to be seen.

Improved Archiving, Cataloging and Distribution of Data As the volume of data increases, the archiving, cataloging, and dissemination of data will become more critical. At the present time, it is often difficult for an individual researcher in one country to even know of the existence of data from a specialized array in another country, let alone obtain copies of the data, until after the data have been discussed in the open literature. Some projects are better than others in this regard. It appears that projects that involve substantial international cooperation do a better job of data dissemination. In addition to the raw measured data, there is a need to make available information on the site characteristics for ground motion arrays or the structure characteristics for structural arrays. Such information should be obtained early on as part of the overall deployment plan and kept on file for future use. A description of the objectives of the array and the reasons for the specific configuration chosen would also be very useful to a potential user of the data.

In the future, better methods will need to be found to catalog and disseminate data and related array information so as to make it more readily accessible. It is likely that the current practice of distributing strong-motion data on either magnetic or optical media will continue, but direct transmission via worldwide data networks may become more popular.

Integration of Ground Motion and Structural Arrays Until recently, ground motion arrays and structural arrays have usually been thought of separately. In the future, greater attention will likely be placed on the interaction between the ground and the built environment. This interaction is not well understood and there are very limited strong-motion data available with which to treat this problem. By integrating ground motion and structural response data into a single system, as with the EPRI experiments in the SMART-1 array, much greater knowledge can be gained on the nature of structural response and soil-structure interaction, as well as on the generation and transmission of waves near the earth's surface. It is felt that greater attention needs to be directed towards this subject in the years to come.

International Decade of Natural Disaster Reduction The United Nations has proclaimed the decade of the 1990's as the International Decade of Natural Disaster Reduction. This presents a unique opportunity for the earthquake engineering and seismology communities to redouble their efforts in earthquake measurement. The International Decade will bring greater attention to the need for and benefits of strong-motion studies. Those involved in strong-motion studies must find ways to capitalize on the increased attention so as to make significant progress towards the goals of understanding the earthquake process and the response of man-made structures. In so doing, it may be helpful to look toward greater interaction with other disaster related technical specialties. It may not be premature to begin to think in terms of a worldwide disaster data network which incorporates data from earthquakes, floods, and winds, as well as other natural disasters. At least the concept should be explored.

CONCLUSIONS

The decade since the Hawaii Workshop has been one of great accomplishment in the area of strong-motion studies. Our ability to measure earthquake generated ground motion and its effect on structures has been greatly enhanced as a result of new instrumentation and the expanded deployment of instruments in arrays and networks. Much valuable data have already been obtained and much more will be forthcoming. We must continue to press ahead in the deployment of arrays and networks. But at the same time, we must strive to achieve greater utilization of the data which are obtained. In the future, the focus of strong motion activities will need to be sharpened to make sure that data obtained are relevant to specific user needs and more effort will need to be directed toward encouraging the greatest possible participation of the user community in the design of experiments.

Considering the new opportunities and challenges which face the strong-motion community, perhaps it is time to convene a follow-up workshop to the 1978 Hawaii Workshop for the purpose of developing a strong-motion strategy for the 1990's. Such a workshop would need to have broad international support if it were to be successful. Comments and suggestions regarding this possibility could be directed to ISMAC through the offices of IAEE.