Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.II)

Key-1

NINE MILESTONES ON THE ROAD TO EARTHQUAKE SAFETY

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SUMMARY

The history of earthquake engineering is reviewed, by surveying the accomplishments of the eight World Conferences. The role of the International Association for Earthquake Engineering in shaping this new engineering discipline is examined. As an illustrative example, the measurement and analysis of strong earthquake ground motion is discussed in terms of early beginnings, current status, and future problems. The need to fully adapt knowledge to widely varying social and economic requirements is emphasized. Although earthquakes still provide many surprises, steady progress has been made towards the ultimate goal of preventing earthquakes from becoming disasters.

INTRODUCTION

My purpose this morning is to celebrate the accomplishments of the International Association for Earthquake Engineering by showing that the history of the nine World Conferences is in fact the history of earthquake engineering itself. A secondary purpose comes from my belief that a review of the history of any subject is a useful way to clarify our perceptions of likely future developments.

For many millenia, mankind has been impressed by the destructive fury of earthquakes, and earthquake engineering in one sense is as old as the first rules of thumb for the design of walls, buildings, and other man-made constructions to resist such forces. Until recently, however, knowledge of the subject has grown primarily by the observation of earthquake effects, unassisted by theories as to the causes and characteristics of earthquakes or by quantitative information on the nature of the damaging earthquake ground motions.

Since the first World Conference in 1956, the subject of earthquake engineering has rapidly evolved from this state of being an experience-based study of past earthquake effects, to its present position as a science-based engineering discipline, with an organized body of knowledge, a research program to add to that knowledge, and a working interaction with the basic sciences of geophysics and seismology on the one hand, and with the practicing design and construction of engineering works on the other.

MILESTONES

First World Conference Many of us here today attended that first World Conference in Berkeley, California, in 1956, and we have watched with fascination the spectacular development from a small group of about forty authors listening to each other present papers, to the present impressively large body of participants. Today's audience contains many of the pioneers who have created modern earthquake engineering, and our present strong position is a tribute to their energy, skill, and perserverence.

It will be instructive to begin with a brief summary of some things that were not known about earthquakes in 1956. First, there was a very incomplete knowledge about the earth's seismicity. It was not until the 1960's that the first world-wide network of standardized seismographs was installed, which for the first time made it possible to provide a reasonably complete global detection coverage for at least the larger earthquakes. There was then no generally accepted theory for the mechanics of earthquake generation, and still a good deal of controversy about the faulting theory of earthquakes. The only quantified source parameter was earthquake magnitude, and there was still much discussion about the significance of various magnitude determinations, which often did not agree very well with each other. Seismic moment and stress drop had yet to be defined. There was no plate tectonic theory to provide a framework for global seismicity, and no paleoseismology to extend our earthquake catalogs backward in time. Only a very few strong-motion accelerograms had been recorded, and most of the earthquakes from which we have learned the most had not yet occurred. It is difficult to remember that in 1956 there were no digital computers to carry our computational burdens. Early models of vacuum-tube type digital computers were just being installed in some university research laboratories, but they were very complicated and expensive devices as yet unavailable for earthquake engineering computations. Finally, it might be mentioned that in 1956 there were no international organizations in the earthquake engineering field and very few national groups engaged in the specialty.

Given this state of ignorance, we might well ask what there was to talk about at this first World Conference? As a matter of fact, much activity was beginning to stir in the field, and a number of key ideas were presented that later resulted in major advances. Reports on new instruments and networks were given; applications of newly formed ideas on response spectrum techniques were explored; methods for inelastic response analysis were discussed; dynamic tests of large structures were examined; and many basic problems of the design of earthquake resistant structures were explored.

Second World Conference The Second World Conference in Japan in 1960 already displayed a dramatic change in the whole situation. For one thing, it launched the establishment of the International Association for Earthquake Engineering. Under the inspiring leadership of Dr. Kiyoshi Muto, a preparatory committee was established, and a sound foundation for our flourishing organization was laid.

At the Second World Conference it was evident that the computer age had arrived. A number of authors reported on research carried out with newly available digital computers, and from that time on the digital computer has been a key factor in every aspect of our work.

At the Second World Conference, the first edition of the publication "Earthquake Regulations of the World" was distributed. This very useful compendium of earthquake resistant codes from various countries was compiled and published by the Organizing Committee for the Conference of the Science

Council of Japan, and reproduced codes and regulations from thirteen countries. This volume has been expanded and reissued for each of the succeeding conferences, having grown to include 34 countries for the Eighth World Conference in 1984.

Another feature introduced at the Second World Conference was a presentation of reports on recent earthquakes. The very destructive earthquakes in Agadir, Morocco and in Chile had just occurred, and preliminary reports on the engineering lessons learned were given. A prompt and detailed survey of earthquake damage, and sometimes lack of damage, has always been a major source of learning about earthquake disasters. Today, partly because of the cooperative links formed by International Association of Earthquake Engineering activities, such investigations are carried out and quickly reported for practically every notable earthquake occurring anywhere in the world. It is of the utmost importance for our subject that suitably experienced personnel and proper organizational arrangements be permanently available to carry out such field investigations in the future.

Third World Conference The Third World Conference on Earthquake Engineering in New Zealand in 1965 had also a number of recent major earthquakes to discuss. The 1963 Skopje, Yugoslavia earthquake, and the notable 1964 Alaska and Niigata, Japan earthquakes provided much food for thought, and many lasting lessons for our subject. The intensive studies of the Alaska and Niigata earthquakes in particular introduced a whole new consideration into earthquake engineering - that of soil liquefaction. Among the technical developments stressed during the Third Conference, it may be noted that the power of the now reasonably available digital computers began to make itself felt, with considerable attention being focused on the structural response of inelastic systems. Problems of the assessment of seismic risk were also beginning to be treated with a good deal more sophistication, and the subject of seismic regionalization played a prominent role.

Fourth World Conference The Fourth World Conference on Earthquake Engineering in 1969 in Santiago, Chile also had its quota of destructive earthquakes to discuss. The Caracas, Venezuela earthquake of 1967 provided many lessons involving soil and foundation response, and the Koyna, India earthquake of 1967 initiated a major world-wide interest in reservoir-induced seismicity, and provided for the first time direct evidence of the effects of earthquakes on large concrete dams and on power plant equipment. From the technical papers presented, it was clear that methods of probabilistic risk assessment were assuming their modern form, studies of random forces and their relationship to the earthquake-excitation problem began to appear, and a considerable amount of work on non-linear and inelastic response problems was reported. The first edition of a new publication of the International Association for Earthquake Engineering appeared just before this Fourth Conference. The "Directory for Earthquake Engineering Research," which has been updated several times since, most recently in 1984, has served as a very useful compilation of organizations and individuals active in our field.

Fifth World Conference Among the notable earthquakes reported on at the Fifth World Conference on Earthquake Engineering in 1973 in Rome were the San Fernando, California 1971 event, with its wealth of strong-motion accelerograms, and the Managua, Nicaragua, 1972 earthquake, which provided a major test of modern construction techniques. The subject of the dynamic testing of structures was featured prominently for the first time. The large shaking table in Berkeley, California, had just been completed, and interesting results of initial tests were presented. Several authors addressed the important problem of deriving basic dynamic parameters of structures from tests. The large number of accelerograms obtained in the upper floors of tall buildings during the San Fernando earthquake had just made it possible for the first time to use naturally occurring earthquakes as meaningful dynamic tests of structures. Another idea explored at this Conference was that of using buried explosions as ground excitations for structural testing. This suggestion has perhaps not been followed up as vigorously as it should have been, for we still do not have the means to carry out dynamic tests of full-scale structures to the point of drastic inelastic behavior and collapse. This lack of experimental data for just that problem that is of the most importance for our subject remains a major handicap for our investigations.

Another indication of the coming of age of our subject was the appearance just before this Fifth Conference of the first issue of the Journal of the International Association for Earthquake Engineering, the periodical "Earthquake Engineering and Structural Dynamics." This has served not only to ensure prompt publication of technical information in the field, but also to help maintain continuity of effort for the International Association between World Conferences. Since that time the expansion of interest in the subject has resulted in several other specialist periodicals which regularly treat of earthquake engineering subjects.

<u>Sixth World Conference</u> The Sixth World Conference on Earthquake Engineering in New Delhi, India in 1977 heard reports on the very damaging 1976 earthquakes in Guatemala and Italy. In that same year the great Tangshan, China earthquake of 1976 had just occurred, the greatest earthquake disaster of modern times. The technical papers of this Conference gave a good deal of attention to the analysis of the rapidly-increasing data bank of strong motion accelerograms, and to the prediction of earthquake ground motion on an empirical basis. Our Japanese colleagues reported for the first time on a new technique for structural testing, that of computer-controlled on-line actuators to carry out programmed load cycles. This pseudo-dynamic testing method has become an important supplement to other test methods, with much promise for the future.

The Sixth World Conference saw the initiation of another publishing activity of the International Association for Earthquake Engineering - the monographs "Basic Concepts of Seismic Codes" were planned and produced. The first volume appeared in 1980, and the second in 1982, both under the sponsorship of the Kajima Foundation and UNESCO. A revised edition of Volume I, Part 2 appeared in 1986 under the title "Guidelines for Earthquake Resistant Non-Engineered Construction."

<u>Seventh World Conference</u> The Seventh World Conference on Earthquake Engineering in Istanbul, Turkey in 1980 opened discussions of several notable earthquakes. Tabas, Iran in 1978, Montenegro, Yugoslavia in 1979, and Imperial Valley, California in 1979, all produced excellent sets of strong-motion accelerograms. Among the technical subjects prominently represented were soil-structure interaction, system identification techniques in structural dynamics testing, and the design of lifeline structures. New aspects of our subject which began to receive increased attention were the economic analysis of earthquake losses, earthquake insurance, and issues of human response to earthquake disasters.

The Seventh World Conference saw the initiation of another activity of the International Association, the formation of the "International Strong Motion Array Council," ISMAC. With the cooperation of a similar committee from the International Association of Seismology and Physics of the Earth's Interior, and support from UNESCO, ISMAC has conducted a number of very successful workshops highlighting important aspects of strong ground motion data acquisition.

Eighth World Conference The Eighth World Conference on Earthquake Engineering in 1984 returned for the first time to one of its former sites - San Francisco. Instead of the forty papers from eleven countries at the First Conference, there were now some eight hundred papers from 54 countries. All aspects of our subject had profited from the large expansion of interest in the field. More and more attention was being applied to the mitigation of earthquake effects, and the subjects of repair, strengthening, and retrofit of older structures were being more systematically studied.

Ninth World Conference Now for the Ninth World Conference on Earthquake Engineering we are returned to Tokyo and Kyoto to repeat the successes of the Second Conference. This is an appropriate place to mention that Japan has in one sense always been the home of the International Association for Earthquake Engineering. Since its inception, the headquarters of the Association have always been in Tokyo, and we are much indebted to the Japan Society for Earthquake Engineering Promotion for the support which makes this central office possible. The detailed business of our Association has been carried out with exemplary efficiency by two outstanding Secretary Generals, first the late Dr. J. K. Minami, and then by the present incumbent, Dr. Yutaka Osawa. Dr. Osawa has conducted our affairs with great effectiveness since the Sixth World Conference in 1977, and we all owe him our deep gratitude for his devotion to our affairs.

For the present Conference, nature has provided us with an unusual abundance of earthquake surprises. Since the first strong motion accelerographs were installed over fifty years ago, we have been waiting impatiently for the first near-source recording of a really great earthquake. This finally occurred in September 1985 in Mexico, where a number of excellent accelerograms were obtained in the epicentral region of a magnitude 8.1 earthquake. To our astonishment, the measured ground motions were much lower than would have been anticipated for the given situation. To compound the surprise, a somewhat smaller earthquake of a similar type occurred in March in Chile, for which considerably larger epicentral ground motions were measured. Unexpected results were also obtained for an earthquake in Nahanni, Canada which occurred in December 1985. First, this magnitude 6.9 event occurred in a region in which earthquakes of this size were thought to be very unlikely, and second, an accelerograph located at the epicenter recorded a peak vertical acceleration of over 2 g, a current world's record. We may hope that these matters will be at least partially resolved by discussions at the present Conference. It is certainly disconcerting to realize that in spite of our vastly increased knowledge of earthquakes, we are still at a stage when so many surprises are possible.

MEASUREMENT AND ANALYSIS OF STRONG GROUND MOTION

Having now briefly reviewed the general history of earthquake engineering by turning the pages of the Proceedings of successive World Conferences, it will perhaps be instructive to examine one subject in more detail, to illustrate the steady progress of our subject. For this example, I shall choose the subject of the measurement and analysis of strong earthquake ground motion.

When seismologists late in the 19th century first acquired the instrumental capability of detecting earthquake waves from any point in the earth, it would perhaps have been expected that there would be a rapid advance in our knowledge about destructive earthquake ground motions. This was not to be, for the interests of the early seismologists turned to the development of sensitive instruments for recording frequently occurring distant earthquakes to enable them to study the internal structure of the earth. Although Japanese scientists and engineers studying the great 1923 Tokyo event were well aware of the need to measure directly the destructive ground motions in the epicentral regions of large earthquakes, and strongly advocated the development and deployment of special instruments for this purpose, it was not until the Long Beach, California earthquake of 1933 that the first direct measurement of a damaging earthquake ground motion was obtained. This was the result of an instrumentation development and deployment project undertaken by earthquake engineers themselves.

At the First World Conference on Earthquake Engineering there were reports on the U. S. Coast and Geodetic Survey network of some fifty specially designed and constructed strong motion accelerographs in the Western United States from which about a dozen important records had been obtained, and on the deployment of the first ten SMAC accelerographs in Japan. We should pay tribute here to the farsightedness of those pioneers who developed these early networks and patiently maintained them over the years. We should also congratulate them on their extraordinary good fortune. Given the small number of instruments available, and the difficulties of deciding where the next earthquakes would occur, an astonishing number of important records were obtained in the first few years of operation. It almost seems as though these early network designers had solved the problem of earthquake prediction!

It was of course generally realized that the few dozen accelerograms that had been obtained by the time of the First World Conference, recorded at sites of uncertain geophysical significance, were far from adequate to define "typical" earthquake ground motions. In closing the First World Conference, in a paper entitled "Summary of Our Present Knowledge of Earthquake Engineering and Some Thoughts on Future Research," the late Professor L. S. Jacobsen, one of the real pioneers of our subject, had this to say: "In general we can agree that the ground motion must start, and it must stop. What it is to be in between start and stop is debatable. All we can say is that it must be an oscillatory motion; it will presumably have many periods in it; and it will have many intensities. Since it is a complicated, relatively long-time motion, it is hard to deal with ...."

This was certainly a cautious, if not discouraging, evaluation of the difficulties of the problem, but help was already on the way. Professor Jacobsen also saw that the recently developing ideas of the earthquake response spectrum, which were reported in several papers at this First Conference, offered a promising way of describing such ground motions that would be particularly significant for structural analysis and design. It was, in fact, in a paper in this same First Conference that Professor Housner presented a set of smoothed average response spectrum curves which, he said, could be "taken to represent the average properties of future strong ground motions." It is interesting to note that these first average response spectrum curves, which are still a very fair representation of earthquake ground motions, were based on just four pre-1952 accelerograms. Among these four earthquakes was the well-known 1940 El Centro event, which has served even to this day as a kind of test input signal for many earthquake engineering applications. It is again our great good fortune that this very early record, only the fourth earthquake to be recorded, turned out to be such an appropriate sample of destructive earthquake ground motion.

Since these beginnings, the expansion of our strong-motion instrumentation networks has been continuous and spectacular. There are now at least 10,000 strong motion accelerographs installed throughout the world, many of them in dense arrays and in down-hole configurations. Some 7,000 of these devices are of the same standard type, simplifying maintenance and comparison of results. Several hundred digital accelerographs of various types are now deployed.

With their advantages of simplicity of data processing, wide dynamic range, wide frequency range, and pre-event memory, these digital accelerographs will no doubt play an ever-increasing role in the future of strong motion measurements. The size of the present world network presents a new set of problems. Even within one country, many different organizations and jurisdictions may be involved in network operations, with consequent problems of data archiving and dissemination. So far there has been excellent success in making available to all investigators all the important accelerograms from any part of the world in a reasonably timely manner, but this is becoming increasingly difficult to do. There is some evidence that there can be significant differences in the results of various data processing methods, so that some type of international standardization will soon become imperative. Problems of this kind are being addressed by the IAEE ISMAC Committee, which will be convening a meeting at the present Conference. With the number of strong-motion accelerograms in our data bank now in the thousands, not only are problems of data collection, archiving, and dissemination becoming pressing, but we are in danger of falling seriously behind in our analysis and study of the available records. It is clear that so much valuable information is contained in this data bank that a much increased effort in studying these records would be highly justified.

EFFECTIVE GROUND MOTION PARAMETERS

The most complete information available on a particular earthquake ground motion is that contained in a broad-band acceleration-time record. Since no ground acceleration record will ever be repeated exactly, one hopes to abstract from many such records those special characteristics which define a "typical" earthquake. By "typical", we mean those characteristics which can be expected to be repeated, within certain limits, at a known level of probability. This has turned out to be an extraordinarily difficult thing to do. We have long since given up the hope that one or two simple parameters, such as peak acceleration, or duration of strong shaking, will be adequate for the purpose. The consequence of the earthquake ground motion which is of most significance to the earthquake engineer is structural failure, and this term "failure" can mean many different things for many different types of structure. A key problem for earthquake engineers is thus to represent the acceleration-time curve by a minimum number of numerical parameters which can be quantitatively related to structural failure, and which will be in a form suitable for design applications and for incorporation in codes and regulations. One current approach to this problem is to define various kinds of "effective" ground motion parameters, where by "effective" one implies whatever modification of measured values is required to make a given parameter directly relevant to structure failure and to structural design. In view of the widely different concepts now being proposed and discussed, it may be important to emphasize certain criteria which should be kept in mind in defining any "effective" ground motion: First, the quantity should be precisely defined, in the sense that from the same acceleration-time curve everyone would get the same numbers. Second, the numbers must correlate with some meaningful structural response. Third, the concept must be appropriate for incorporation into codes, design standards, etc. By such standards, there exists now no universally recognized approach to this effective ground motion problem, the solution of which is a major goal for the future.

STRONG MOTION SEISMOLOGY

One interesting consequence of the efforts which have been made by earthquake engineers to measure and to understand strong ground motion has been the development of a new branch of seismology called "strong motion seismology." After the excellent set of accelerograms were obtained by an instrumental array close to the causative fault during the Parkfield, California 1966 earthquake, seismologists began to realize that such near-field records would be of key importance for the investigation of earthquake source mechanisms. Since then many accelerograms have been obtained in the near-source region, and theoretical seismology has had considerable success in synthesizing such records from inferred details of fault fracture, and in illuminating many aspects of the mechanics of earthquake generation. The 1983 U. S. National Report on Seismology to the International Union of Geology and Geophysics included for the first time a section on strong motion seismology, which is now a vigorously pursued branch of the subject. Since the ultimate goal of strong motion seismology is to predict strong ground motion from an understanding of the basic principles of fracture mechanics and wave propagation, this science has much of direct practical relevance for earthquake engineering. These developments have strengthened historic bonds between seismology and earthquake engineering which has been of much mutual benefit.

Another problem in which seismologists and earthquake engineers have cooperated very closely is that of seismic risk assessment. By bringing together information from tectonics, geology, and such seismological topics as the mechanics of earthquake generation, wave propagation in inhomogeneous media, effects of local geology, etc., and by treating the many uncertainties involved within a probabilistic framework, it has been possible to compare the seismic risk at various places in the world on a reasonably quantitative basis. It was the design of critical structures such as nuclear power plants, dams, and hospitals that provided the initial stimulus for much of this work which is now assuming an important role in establishing ground motion criteria for regulatory and design purposes. Even though it is still difficult to agree on the absolute values of a given ground motion parameter to be expected at a particular site, patterns of behavior can be delineated and the sensitivity of the results to various uncertainties can be approximated.

As we examine the large number of strong-motion accelerograms now available, along with supporting data from geology, geophysics, and seismology, we are much impressed by the fact that earthquakes are much more different from one another than had previously been supposed. The whole process of the generation and transmission of earthquake waves is clearly much more complex than we had at one time hoped. It is now evident that some clearly-defined faulting systems must be thought of as being composed of smaller segments, each associated with earthquakes of a characteristic size. The fracture process itself is usually a complicated series of events involving several discrete sources, and various patterns of fracture propagation which can have a major effect on the directions and amplitudes of the propagated waves. The high-frequency wave generation which is of direct relevance to earthquake engineering is critically dependent on various inhomogeneities of the fracture process, which can be modelled by assuming various distributions of strong or weak zones, often referred to by seismologists as asperities or barriers. We had hoped that if we were to specify magnitude, distance, and perhaps a simple parameter related to local site conditions, we could achieve a meaningful prediction of expected ground motion. As the number of actual measurements of earthquake ground motion grow, it is becoming clear that the number of basic parameters must increase if we wish to deal effectively with the disconcertingly large dispersions of the measured values.

The preceding remarks have been focused on the specific subject of ground motion measurement and interpretation to serve as an example of the kind of steady evolution that has marked all aspects of our field of earthquake engineering. Similar patterns of development could be followed through for dynamic testing of structures, for structural analysis and design, for soils and foundation problems, for lifeline system design, for codes and regulations, for social and economic effects, and for all other elements of our subject.

CONCLUSIONS

In looking back over the accomplishments of the International Association for Earthquake Engineering, one fact is of special interest to the present gathering, and that is the extent to which earthquake engineering has always been a truly international undertaking. Natural hazards such as wind, flood, famine, fire, and earthquakes know no national boundaries, and knowledge gained in one part of the world is often directly applicable elsewhere. Of all the investigators of natural disasters, earthquake engineers were perhaps the first to clearly recognize the value of international cooperation, and to provide the necessary organizational framework to assist it. This may be the reason why Dr. Frank Press, President of the U. S. National Academy of Sciences, chose a keynote address to the Eighth World Conference on Earthquake Engineering in San Francisco in 1984 to present his vision of an "International Decade of Natural Hazards Reduction," which we will no doubt hear more about during the course of the present Conference.

At this stage of our history, it is also a good time to question the overall effectiveness of our work. To what extent have our efforts helped to reduce the threat of earthquakes? How far along the way are we towards preventing earthquakes from becoming disasters? We must hasten to admit that we are far from our goal. In the four years since the Eighth World Conference there have been about 12,000 earthquake fatalities in 39 countries. Although this total is well below the average for this century, of some 15,000 earthquake deaths per year, we are still obviously confronted by a staggering human problem, and we must re-double our efforts to translate knowledge into earthquake resistant structures all over the globe. We must express our deepest sympathies for the victims of the recent tragedies in Mexico, Chile, and San Salvador, from which we learn again how difficult it is to realize in actuality the improvements that we should be in a position to implement. In each of these events, however, there are numerous examples of well-engineered, well-constructed structures which survived with little or no damage. This can give us hope that we are at least moving in the right direction. We must never forget that even now a large fraction of the world's population must live and work in structures which cannot be expected to safely withstand earthquake forces. Much of what we have been considering as we have been surveying the development of our field has involved the scientific and theoretical aspects of our subject. Even more significant for our main goals is the full implementation of our knowledge, within many different social and economic settings. From land use planning, through earthquake resistant design and construction, and including appropriate responses to disaster through community organization, we must always keep in mind the human dimensions of our undertaking.

In conclusion, I should like to thank the Organizing Committee of the Ninth World Conference on Earthquake Engineering for this opportunity to present my views. I am proud of the International Association for Earthquake Engineering, and am very pleased to have had a small part in its activities. May I also express my hopes and expectations for the present Conference, which I am sure will become one more important milestone on the road to earthquake safety.