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EARTHQUAKE RESEARCH PROBLEMS OF NUCLEAR POWER GENERATORS

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ABSTRACT

Earthquake problems associated with the construction of nuclear power generators require a more extensive and a more precise knowledge of earthquake characteristics and the dynamic behavior of structures than has been considered necessary for ordinary buildings. Economic considerations indicate the desirability of additional research on the problems of earthquakes and nuclear reactors. The nature of these earthquake-resistant design problems is discussed and programs of research are recommended.

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Introduction

The development of nuclear reactor electric power generators has involved many unique engineering features which distinguish this field from the ordinary industrial processes with which we are familiar. One noteworthy feature of nuclear power is the very short interval between the initial discovery of controlled fission and its practical application to power generation. From the first atomic pile to the construction of non-experimental nuclear electric power generating plants required

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less than twenty-five years. This is a remarkably short time for engineering development in view of the highly sophisticated scientific and technical problems involved.

The potential hazard of uncontrolled release of radioactive material into the atmosphere has from the beginning posed a special problem in reactor safety. There are, of course, many other industrial processes involving materials of potential hazard to human life, and these industries are also faced with problems of safety. However, the attention given to the safety of nuclear reactors by technical experts is undoubtedly far greater than for any other industrial process. There has even developed a new profession of reactor safety, the members of which are expert in the various potential hazards and their avoidance. A new vocabulary has been developed to describe concepts of hazard and safety that prior to this time had hardly been contemplated. Examples of such new terms pertinent to our present problem are: maximum probable incident, maximum credible incident, maximum conceivable incident, scram, seismic scram, and total scram. The reactor safety experts have developed methods of analyzing the effects of malfunctions, failures, accidents, etc., with a view of providing appropriate safeguards.

The concern of the public over hazards of nuclear reactors, and also the concern of various governmental agencies, is much greater than might have been anticipated. This is no doubt in large measure due to the extensive publicity given to the effects of nuclear weapons and the conscious, or unconscious, association in the mind of the public of nuclear power plants with the hazards of nuclear weapons.

The importance of eliminating possible hazards in the operation of nuclear power generating plants has led to designs where considerations of safety are paramount. In fact, it has been suggested that the designs are overly safe and, hence, overly costly. This may well be true, but by the very nature of the problem, this overdesign is at present unavoidable. The reason for this can be explained by means of a very simple example. Suppose a bridge is to be designed to be safe in the ordinary sense. The loading conditions and the allowable stresses to be used in the design will be specified by the code, and a design can be made that incorporates a factor of safety based on past experience of many similar structures. It should be kept in mind, however, that the factors specified in the code represent merely the consensus of the committee that drafted the code, and that the true "factor of safety" is not clearly defined. On the other hand, suppose that there were no applicable codes or past experience and the bridge was to be safe in the sense that a nuclear power generator is safe. In this case the design would have to take into account the maximum probable load which might be the heaviest truck that is known to travel in that region, and the maximum credible load which might be the heaviest wheeled vehicle in the entire country. The design must also take into account the maximum probable (MP) and maximum credible (MC) vehicle velocities as well as the MP and MC variations in material properties and foundation conditions. The MP and MC floods, winds, temperatures, etc., must also be accounted for in the design. The possibility of an out-of-control vehicle such as a truck, airplane or ship crashing into the bridge structure is a credible incident and must be taken into account. Such considerations will obviously lead to a very conservative design.

The MP and MC values and likelihood of occurrence can usually be specified only in a more or less approximate probability sense and the nature of the available information will have a most important influence. A type of uncertainty principle is involved which states that the less certain one is of the facts the more conservative and costly must be the design. This is illustrated by the two probability curves shown in Fig. 1. In A is shown the curve one might obtain when all of the pertinent facts are known; the curve in B might represent the same situation when there is uncertainty about the facts. In A, the MP and MC are easily located whereas in B their proper location is far from obvious. In fact, the assumed MP and MC in B must be located beyond their true positions, as shown in A, because of the uncertainty. If, for the bridge, there are a half-dozen design factors subject to such uncertainty, and the design is to be safe in the nuclear reactor sense, it will be necessary for the bridge to be overdesigned and overly costly. To avoid this, it is necessary to reduce the uncertainties by developing more precise information about the factors pertinent to the problem.

Although design of ordinary structures involves many of the same uncertainties encountered in the nuclear power generator design, the problem is usually simplified by adopting the following point of view. It is supposed that in the unlikely event that the MC incident should occur, a moderate expenditure would be required to repair the damage. It is usually concluded that it is not economically justifiable to spend an appreciable amount of money initially to forestall the cost of future repairs required by an event which has a small probability of occurrence. It is obvious that such a basic design philosophy is not appropriate for nuclear reactors; for these, all of the uncertainties in loading conditions, material properties, etc., must be covered by extra factors of safety.

At present, earthquake design criteria for nuclear power generators are three to six times more severe than those specified by the building codes for ordinary structures. If only a few nuclear power plants were to be built it might be argued that the cost of the extra factors of safety would not exceed the cost of the research required to reduce the uncertainties to a more economical level. However, if nuclear power generators continue to be used in greater numbers in the future, the cost of eliminating the chief uncertainties and thus achieving more economical designs will be much less than the cumulative cost of providing large factors of safety.

1. Nuclear Reactors and Earthquakes.

The occurrence of strong earthquakes in many regions of the world poses special problems of safety in the design and construction of man-made works. In addition to the matter of public safety, there is also a monetary aspect involved since it is not economically feasible to design all ordinary structures to resist without some damage the greatest earthquake, which may be only a once-in-a-thousand-years event. To allow for this, the requirements of building codes in California are based on the premise that buildings should survive without damage the moderately strong ground motions whose probability of occurrence is relatively high,

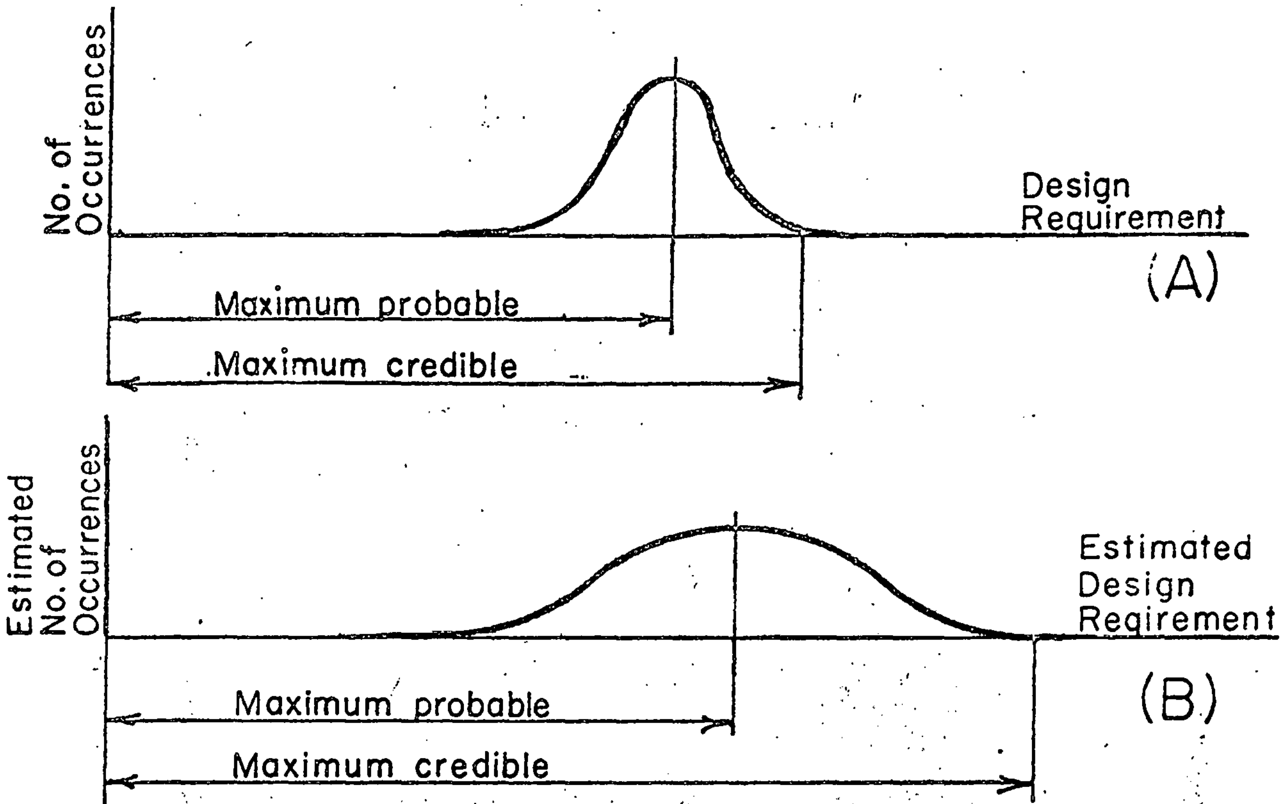
No. of Occurrences
Design Requirement
(A)
Maximum probable
Maximum credible
Estimated No. of Occurrences
Estimated Design Reqirement
(B)
Maximum probable
Maximum credible

FIG. 1

but that some damage will be tolerated in the event of large and relatively infrequent earthquakes. This philosophy of design is in direct contradiction to that used in designing nuclear power generators[1, 2, 3].

In the past, research in engineering seismology has been directed mainly at the problems of designing ordinary structures such as are found in large cities, in particular, Los Angeles, San Francisco, and Tokyo. As a consequence, the problems of designing special structures to withstand great earthquakes without suffering even slight damage has not been given particular study. Because of this the knowledge of earthquake factors is not as precise as would be desirable. No one of the earthquake factors pertinent to the design is subject to large uncertainties but the conservatism required to cover a number of small uncertainties can have an appreciable economic effect. The existing body of information should now be extended and made more precise by research whose breadth and depth are suited to the special requirements of nuclear reactor facilities. Some of the special requirements related to nuclear applications are:

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[1] R. Hicks and I. A. B. Grant, The Seismic Design of a Nuclear Power Station in Japan, Proc. 2nd World Conference on Earthquake Engineering, Tokyo, 1960.

[2] G. W. Housner, Design of Nuclear Power Reactors Against Earthquakes, Proc. 2nd World Conference on Earthquake Engineering, Tokyo, 1960.

[3] K. Takeyama, Earthquake Resistant Design for Nuclear Power Plants in Japan, Proc. Symposium on Reactor Safety and Hazards Evaluation Techniques, International Atomic Energy Agency, Vienna, 1962.

(1) The general level of safety which is demanded of an earthquake-resistant design is closely related to the consequences of failure. The desire to eliminate any possibility of failure of certain components in a nuclear installation means that many uncertainties which could be accepted in ordinary structural earthquake-resistant work cannot be tolerated in nuclear design. A more precise knowledge of earthquake phenomena is required than has been available, and theories which have in the past given acceptable accuracies must now be extended to attain an increased certainty.

(2) Special structures are often encountered in nuclear plants which are outside usual experience. In such special structures, there is little guidance from past practice, and information as to the behavior of such structures in past earthquakes is not available. Examples are graphite-block assemblies for gas-cooled reactors, complex cooling systems and control systems.

(3) The design of the structures may be much influenced by the requirements of the nuclear processes themselves, which may dictate types of materials as well as shape and size of structural members. For example, materials might have to be limited to those having low neutron absorption cross-sections.

(4) The behavior of materials under the conditions encountered at certain critical points in a reactor assembly may be important in the design. The effects of strong radiation fields on structural properties of materials is an item which may be important in future designs.

(5) The necessity for remote control of many processes, and for safety devices, results in an inter-relation between structure and

mechanism which may impose special limits on deflections or other structural responses.

(6) The problem of the effects of transient forces on fluid motion become of critical importance in some applications, such as cooling systems and emergency water supplies.

(7) The development of seismic detection and warning systems, as well as automatic shut-down devices, becomes of importance.

(8) Nuclear reactors are usually erected at some distance from a city on sites where the local geology may be quite different from that within the city which has been studied from the point of view of its influence on the earthquake response of structures. Since the number of good sites is limited it will eventually be necessary to build reactors on sites where geology is less favorable.

The consequences of these new conditions are that an increased research effort must be made to extend the scope and improve the precision of our knowledge of the facts pertinent to all of the ordinary problems of destructive earthquakes and, in addition, special investigations related particularly to nuclear installations must be undertaken.

2. Current Problems in Earthquake Engineering for Nuclear Power Plants.

The fundamental problems of earthquake engineering as they relate to nuclear power plant design may be summarized as:

(A) Prediction of the maximum expected ground motion at a particular site.

(B) Description of typical strong earthquake ground motions from the standpoint of their effects on structures.

(C) Calculation of structural response to earthquake forces, including under structure such special components as piping systems, containment vessels, control rod assemblies, electrical switches, etc.

(D) Determination of the actual dynamic properties of structures.

(E) Design of structures, equipment, and components to successfully withstand earthquake forces.

Each of these major areas will be discussed in some detail, to indicate the specific research projects which are at this time justified by past background and future requirements.

3. Prediction of Maximum Expected Ground Motion.

The maximum earthquake ground motion to be expected at a particular site will depend upon: (a) the general seismicity of the region, which will indicate the probability of earthquakes of a given magnitude occurring within specified intervals of time at various epicentral distances; (b) local geological conditions, such as the existence of active faults in the vicinity; and (c) local soil and foundation conditions in the immediate neighborhood of the installation.

Considering first item (a), the basic information on seismicity is derived from many sources, including teleseismic recordings at distant sensitive seismograph stations, strong-motion accelerograph recordings, studies of earthquake damage, and post card surveys. In the past, the most important information has been that obtained from teleseismic recordings, usually made by seismologists in connection with studies of the internal constitution of the earth. Networks of high-magnification seismographs have been established throughout the world for this purpose, and these networks are at present being expanded by a large program sponsored by the United States Government which involves the installation of several hundred new seismographs in various regions of the globe not previously covered. These instruments are adequate to detect the occurrence of intermediate sized earthquakes at any point in the earth, and to permit an approximate calculation of location and size. The engineer may thus expect from the seismologist basic data on the frequency of occurrence of earthquakes of various sizes in most parts of the world. The detailed character of the forces involved, and the ways in which such forces may be modified by local conditions, must be investigated by the engineers themselves, since this aspect of the subject is of relatively little interest to the seismologist.

Item (b), involving local distribution of seismicity, touches on a problem which requires extensive additional study. The number of seismographs available in the world has never been large enough to permit detailed studies of local effects. It is known that ground motion may be modified by features of local geology, but no generalizations have yet emerged which are satisfactory for precise predictions of expected ground motion in a location of complex local geology. Several types of instrumental programs which would make important contributions to this subject are: (1) Sets of portable, intermediate sensitivity, short-period seismographs which could simultaneously record the same earthquake at various points in a region, should be installed and operated for periods of several months at many representative sites. By installing six such instruments in various geological environments in an area of some 100 sq. mi., and recording a number of small, nearby, natural earthquakes, a considerable increase in our knowledge could be quickly realized. Such studies were started in 1956 in southern California[4], but are no longer being actively pursued. Similar studies have been made in Japan and Russia, but in no country have they been sufficiently complete to cover areas of potential interest as sites for nuclear installations, nor has a correlation been established with the ground motion of large earthquakes; (2) The measurement of microseisms and microtremors with high sensitivity seismographs may yield comparative data of value. Studies of this type have been made in Japan[5]. Such microtremor measurements can be made much more frequently than earthquake measurements, and if correlations can be found between the relative local behavior of these very small ground motions and the effects of the much larger ground motions caused by damaging earthquakes, an important new tool will be available for engineering studies. (3) Most important for earthquake engineering is a rapid expansion of the number of strong-motion accelerographs for the measurement of damaging earthquake ground motions. Without these strong-motion acceleration measurements, no scientific study of earthquake damage or earthquake-resistant design is possible. When it is realized that in none of the recent destructive earthquakes throughout the world, such as Mexico (1957),

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[4] B. Gutenberg, Effects of Ground on Earthquake Motion, Bull. Seism. Soc. Am., Vol. 47, No. 3, July 1957.

[5] K. Kanai, T. Tanaka and K. Osada, Measurement of the Microtremor, Pt. I et seq., Bull. Earthquake Research Institute, Vol. 32, No. 2, July 1954.

Morocco (1960), Chile (1960), Iran (1962) and Skoplje (1963) has there been even one measurement of the strong ground motion, it will be seen how opportunities for basic data are being wasted. So far, ground motions near the centers of large earthquakes have been recorded only in the United States. It is not known whether or not the ground motions in other parts of the world have the same characteristics as those in the United States. It is usually presumed that they do but this is a point needing additional research. Even in the United States the strong ground motions of most potentially damaging earthquakes (Magnitude 5.5 or greater) are not recorded because no instrument happens to be in the epicentral area. Every nuclear installation, or its site, in the United States or elsewhere in the world, should be instrumented with a strong-motion accelerograph so that there will be a precise knowledge of the ground motion to which it has been subjected. (4) Additional sources of ground-motion data which should be more fully exploited are quarry blasts and underground nuclear detonations. Since the location and time of such blasts are accurately known beforehand, instruments can be located at optimum sites for ground motion studies and can be operated in such a way as to obtain maximum information from these artificial earthquakes. Such blasts have been used to a minor extent in the past, and such studies as have been made show a useful correlation between the damage caused by earthquakes and blasts[6,7].

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6 D. E. Hudson, J. L. Alford and G. W. Housner, Measured Response of a Structure to an Explosive Generated Ground Shock, Bull. Seism. Soc. Am., Vol. 44, No. 3, July 1954.

7 A. T. Edwards and T. O. Northwood, Experimental Blasting Studies on Structures, Hydro-Electric Commission of Ontario, and the National Research Council, Ottawa, Canada, January 1958.

Item (c) involving local soil and foundation conditions touches on one of the most important unknowns in the earthquake engineering field. Studies of damage caused by earthquakes have demonstrated the importance of soil and foundation conditions[8], but quantitative assessment of the problem has been made difficult by the lack of basic data as to the dynamic properties of soils. Fundamental work on the dynamic aspects of soil mechanics needs to be much expanded and special studies related to the earthquake damage problem will need to be initiated.

4. Description of Strong Earthquake Ground Motions.

The basic data needed for studies of the effects of earthquakes on structures are the accurate records of the ground acceleration versus time for actual destructive earthquakes, measured on ground conditions similar to those on which engineering structures are to be located[9]. It is important to note that the standard seismographs used by seismologists for their studies of earthquake phenomena are not suitable for this purpose. The reasons for this are as follows: (a) Most seismologists in the past have been primarily interested in distant earthquakes involving wave propagation paths through the central parts of the earth or along the continental structures. Sensitive instruments have thus been developed which will record small shocks originating thousands of miles away. Large destructive shocks in the near vicinity of most standard seismographs will

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[8] C. M. Duke and D. J. Leeds, Response of Soils, Foundation and Earth Structures to the Chilean Earthquakes of 1960, Bull. Seism. Soc. Amer., Vol. 53, No. 2, February 1963.

[9] D. E. Hudson, The Measurement of Ground Motion of Destructive Earthquakes, Bull. Seism. Soc. Am., Vol. 53, No. 2, February 1963.

render them inoperative or will give off-scale readings. The remedy for this situation is to design dual-scale or logarithmic instruments, or to supplement the sensitive seismographs with special strong-motion seismographs of reduced sensitivity. At the present time, few seismological laboratories in the world are well equipped in this respect. (b) Most of the studies hitherto carried out by seismologists have required only the measurement of the arrival times of seismic disturbances, from which the velocities of propagation could be determined. For this purpose it is not required that the seismograph should record true ground motion, and in the interests of increased sensitivity such seismographs are usually designed in such a way that true ground acceleration cannot be accurately determined from the records. The instrument periods are in general too long, and the recording speeds too low, to permit the type of measurement needed for engineering purposes. The response of a structure to an earthquake ground motion can be determined only if the true ground acceleration is known to a relatively high degree of accuracy. Accelerations cannot be obtained from velocity or displacement records with this required accuracy, because of the errors associated with any feasible method of differentiating. (c) Seismologists have usually been primarily interested in the earth as a whole, and most seismographs are located on bedrock to eliminate or reduce the influence of local crustal irregularities. The engineer, on the other hand, wishes to know the conditions at the sites at which structures are to be erected. For this reason the recording instruments must often be placed in alluvial regions which may be influenced by local geology and soil conditions. Since local conditions may vary rapidly over a region, a relatively large number of instruments would have to be installed in the regions of primary interest if the effect of local geological conditions are to be understood.

It will be evident from the above remarks that the instrumentation maintained in the present networks of seismographic stations in the various countries will not be adequate for the needs of earthquake engineering. Although much useful information as to the seismicity of various areas of the world can be obtained from such stations, so that important studies of the probabilities of occurrence of earthquakes in time and space can be made, the engineers themselves must expect to establish additional stations to record the true ground motion of strong earthquakes.

A strong-motion accelerograph for earthquake measurements should have the following properties[9]: The basic transducer element should have a natural period less than 0.1 sec., preferably about 0.05 sec., so that it will serve as an accelerometer for all important ground periods. The instrument should read a peak acceleration of about 1g, with a record size such that accelerations of 0.01g can be accurately measured. A recording speed of at least 1 cm/sec is required to give the necessary detail in the record. This is a sufficiently high speed so that continuous recording is impracticable, and thus a starting device actuated by the earthquake itself is required. The recording system should be arranged so that after starting, a record length of 2-3 minutes is obtained, after which the mechanism will shut down automatically and reset itself to repeat the sequence of events. A sufficient supply of recording material is necessary so that a number of earthquakes can be recorded without servicing the instrument.

The starting system is the most critical part of a strong-motion accelerograph. If the starter is too insensitive, small earthquakes may be missed entirely, and excessive time delays in starting may cause difficulties for large earthquakes. If the starter is too sensitive, it may be set off by extraneous non-seismic vibrations or by a series of small earthquakes, with the danger that the recording paper supply is exhausted before a strong earthquake occurs. It is evident that this starter problem is the same as the problem of designing an earthquake-operated warning or shut-down switch. Thus the accelerograph design is closely related to the "seismic scram" problem.

One of the most pressing problems is the extension of the network of strong-motion accelerographs throughout the highly seismic regions of the world. In only two relatively small regions, California and Japan, are there an appreciable number of accelerographs. By far the larger portions of the earth's major earthquake zones are not provided with suitable strong-motion instrumentation and many sites of potential interest to the nuclear power industry are not covered.

5. Calculations of Structural Response to Earthquake Forces.

The earthquake ground acceleration is one of the loading conditions for the design of nuclear power plants, and the maximum stresses and strains produced in the various structures and equipment by the ground motion must be determined[10]. This is a rather complex problem in dynamics, one of whose difficulties arises from the fact that the earthquake ground motion is very irregular and cannot be described by any simple analytical expression. In addition, actual machine and building structures have complex nonuniform distributions of mass and stiffness. A vibration analysis of such a complex system requires elaborate calculations involving the most modern computing equipment. The accuracy of the results is much influenced by the uncertainties involved in specifying the physical properties of the system and in simplifying an actual structure to the point where an analysis is at all practical. Additional research must be done before precise vibration analyses can be made of nuclear power plant systems without the expenditure of excessive time and effort.

For purposes of design the dynamic response of structures during earthquakes is usually approached from the point of view of the Earthquake Response Spectrum[11, 12, 13]. Some of the results which have been obtained

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10 G. W. Housner and D. E. Hudson, Vibration of Structures Produced by Seismic Waves, Shock and Vibration Handbook. McGraw-Hill (1961).

11 G. W. Housner, R. R. Martel and J. L. Alford, Spectrum Analysis of Strong Motion Earthquakes, Bull. Seism. Soc. Am., Vol. 43, No. 2, April 1953.

12 D. E. Hudson, The Response Spectrum Technique, Proc. 1st World Conference on Earthquake Engineering, Earthquake Engineering Research Institute, 1956.

13 D. E. Hudson, Some Problems in the Application of Spectrum Techniques to Strong Motion Earthquake Analysis, Bull. Seism. Soc. Am., Vol. 52, No. 2, April 1962.

from a study of the response spectrum curves for past Pacific Coast earthquakes can be summarized as follows: (a) An approximate method which is often used in earthquake-resistant design is to replace the actual earthquake accelerations by an "equivalent" set of static lateral loads. Since the actual accelerations of buildings may be considerably larger than the ground accelerations, the proper values of these equivalent static loads can be determined only on the basis of a dynamic analysis. The response spectrum curves give directly the correct effective values of these lateral loads for simple structures. (b) A study of the response spectrum curves have shown that a major consideration in limiting peak structural accelerations is the energy dissipation within the structure. Anything that can be done to appreciably increase the energy absorbed by the structure will increase earthquake resistance. (c) It has been found that many of the features of Pacific Coast earthquakes can be duplicated by supposing that the earthquake ground motion consists of a mathematically random function[14, 15, 16, 17].

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14 G. W. Housner, Characteristics of Strong Motion Earthquakes, Bull. Seism. Soc. Am., Vol. 37, No. 1, January 1947.

15 J. L. Bogdanoff, J. E. Goldborg and M. C. Bernard, Response of a Simple Structure to a Random Earthquake-Type Disturbance, Bull. Seism. Soc. Am., Vol. 51, No. 2, April 1961.

16 E. Rosenblueth and J. I. Bustamante, Distribution of Structural Response to Earthquakes, Proc. Am. Soc. Civ. Eng., Vol. 88, No. EM3, June 1962.

17 P. C. Jennings, Response of Simple Yielding Structures to Earthquake Excitation, Report of Earthquake Engineering Research Laboratory, California Institute of Technology, 1963.

18 G. W. Housner, Behavior of Structures During Earthquakes, Am. Soc. Civ. Eng., No. EM4, October 1959.

This fact makes it possible to apply the techniques of statistical analysis to the earthquake problem. (d) The response spectrum curves for different earthquakes show many common features, to the extent that it has now been possible to prepare a set of "average spectrum curves" which will give a good approximation for typical Pacific Coast earthquakes[18]. (e) The velocity response spectrum curves are directly related to the energy in the structure, and can thus serve as a starting point for limit design methods. Such methods may provide a rational strength criteria for earthquake excited structures which may be strained into the plastic range[19].

The application of response spectrum techniques to complicated structures involves certain approximations which need to be more completely understood. For example, the way in which various modes of vibration excited by an earthquake may combine in a structure needs further study. To attain the greater accuracy demanded by nuclear applications will require a refinement of the analytical techniques now used in response spectrum applications.

In addition to the above response spectrum studies, numerous more involved structural situations have also been analyzed, including some studies of nonlinear structures under yielding conditions[20, 21, 22, 23, 24]. In order to

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19 G. W. Housner, Limit Design of Structures, Proc. 1st World Conference on Earthquake Engineering, Earthquake Engineering Research Institute, 1956.

20 J. Penzien, Elasto-Plastic Response of Idealized Multi-Story Structures Subjected to a Strong Motion Earthquake, Proc. 2nd World Conference on Earthquake Engineering, Tokyo, 1960.

21 A. S. Veletsos and N. M. Newmark, Effect of Inelastic Behavior on the Response of Simple Structures to Earthquake Motions, Proc. 2nd World Conference on Earthquake Engineering, Tokyo, 1960.

22 K. Muto, et al., Non-Linear Response Analysis of Tall Buildings to Strong Earthquake and its Application to Dynamic Design, Eng. Research Inst. University of Tokyo, 1962.

23 G. V. Berg and S. S. Thomaides, Energy Consumption by Structures in Strong Earthquakes, Proc. 2nd World Conf. on Earthquake Eng., Tokyo, 1960.

24 R. Tanabashi, Nonlinear Transient Vibrations of Structures, Proc. 2nd World Conf. on Earthquake Eng., Tokyo, 1960.

use the results of response spectrum analysis for the design of complicated multi-degree-of-freedom structures, studies have been made of the ways in which the responses of the various modes of vibration add up in the total response[25,26]. Many additional studies of this kind are needed, particularly for systems loaded into the plastic range, for which the very complicated theory of nonlinear mechanics is required.

The availability of modern high-speed computing techniques opens up new possibilities for dynamic studies. Such studies require, however, the largest types of digital and analog computers, and hence tend to be expensive. To fully exploit such modern computing techniques in the field of structural dynamics as applied to the design of nuclear power plants will call for a greatly increased support of this work, and a greatly increased number of highly qualified investigators.

6. Determination of the Actual Dynamic Properties of Structures.

Relatively little research has been done on the behavior of actual full-sized structures subjected to dynamic loads. It has been difficult to learn much from tests of small models because of uncertainties as to the behavior of such details as joints and connections, and because of the inherent inhomogeneities of many common structural materials such as reinforced concrete. It thus appears that for earthquake resistant design purposes, much more work must be done involving dynamic tests at high load levels of actual full-scale structures and of large models.

There is still much to be learned on a fundamental level by laboratory investigations of individual structural elements. For many common

[25] H. C. Merchant and D. E. Hudson, Mode Superposition in Multi-Degree-of-Freedom Systems Using Earthquake Response Spectrum Data, Bull. Seism. Soc. Am., Vol. 52, No. 2, April 1962.

[26] R. W. Clough, Earthquake Analysis by Response Spectrum Superposition, Bull. Seism. Soc. Am., Vol. 52, No. 3, July 1952.

structural elements the relations between actual behavior and that predicted by standard design theories has not been satisfactorily established. The effects of even such simple dynamic loads as repeated alternating loads, which can be applied in the laboratory with relative ease, have not been thoroughly studied.

Of primary importance, however, are dynamic tests made on actual full-scale structures. In one general category of dynamic test, the linear dynamic properties of the structure are of major interest. This implies relatively small displacements, and hence no consideration of structural failure is usually involved. The major parameters desired are the natural frequencies of vibration of all significant modes, the corresponding mode shapes, and the amount of energy dissipation or damping associated with each mode.

In the second category of test, are studies of nonlinear behavior, such as investigations of yield conditions, and the determination of energy dissipation under such yielding. Included in this category are studies of criteria of failure, and of failure details involving excessive yielding, fracture, impact, and fatigue.

Perhaps the most important type of structural dynamic test is the steady state resonance test. Ideally such a test would be carried out by applying sinusoidal forces of constant amplitude and adjustable frequency to the structure, distributing these forces throughout the structure in such a way as to excite a pure normal mode. By measuring steady state system response at various frequencies, the resonance curves can be defined, from which the natural frequencies and the damping can be determined.

Resonance curves may also indicate by their shapes the basic nature of the restoring force and damping force mechanisms, particularly for nonlinear systems. Resonance curves obtained for a series of exciting force magnitudes will also give considerable information about the nonlinear properties of the structure.

Because of the special importance of resonance testing for accurate investigations of structural response, special efforts have been made to produce a precision variable frequency sinusoidal force generator for structural vibration tests. A project to develop such a vibration generation system has recently been completed[27]. This force generation system can exert a total inertia force of 20,000 lb with a precise frequency control. With such a system it is possible to excite actual full-scale structures into relatively large vibratory motions. A novel feature of this force generation equipment is that it consists of four mechanical rotating-mass oscillators each of 5000 lb capacity, and each with an electronic-amplidyne speed control and synchronization system. This multiple unit feature makes it possible to excite various modes of vibration, such as torsional modes, and to distribute the exciting forces throughout the structure in an efficient way. This vibration generation system is now in a complete form and is available for test programs. Much information on dynamic properties of structures of direct use to the nuclear power industry could be obtained by such tests, and it is to be hoped that support for such investigations will be forthcoming. Considering the present almost complete absence of

[27] D. E. Hudson, A New Vibration Exciter for Dynamic Test of Full-Scale Structures, Report of Earthquake Engineering Research Laboratory, California Institute of Technology, September, 1961.

accurate resonance test data on structures, the amount of useful work that could be accomplished by this new system is almost unlimited.

It has occasionally been possible to test structures under transient conditions imposed by ground motions caused by blasts and earthquakes. Large quarry blasts are sometimes located sufficiently close to buildings so that significant structural stress levels are attained, and simultaneous measurements of ground acceleration and building response will make it possible to calculate some structural parameters under actual transient dynamic loads. The possibilities of such blast motion studies have not been fully exploited for structural tests, and considerable additional information could be obtained in this way by a better coordination and planning of blast tests that are being organized primarily for other purposes. The possibility of special blast tests primarily for structural dynamic tests should also not be overlooked, as this may be one of the best ways of producing realistic transient dynamic forces for large test structures.

Mention should also be made of large shaking table tests. Although such shaking tables are usually used for model testing, some of them are of a size suitable for small structures or for full-scale structural components. One shaking table in Japan, for example, can apply an exciting dynamic force of 56 tons to a load of 22 tons. Such large machines have so far not been used in the United States, but the possibilities of this type of testing should be kept in mind.

A number of multi-story buildings in Los Angeles and San Francisco have been instrumented by the U. S. Coast and Geodetic Survey with recording strong-motion accelerographs in both basement and upper story locations. From simultaneous measurements of ground motion and building response during strong earthquakes, considerable information on the dynamic characteristics of structures can be obtained. An increased availability of an improved strong-motion accelerograph, as advocated above for earthquake ground motion studies, would permit the building instrumentation program to be expanded. It would be very desirable, for example, to instrument some existing nuclear installations in this way, so that if a strong earthquake should occur in the vicinity, a direct record of the behavior of some of the special structures involved in nuclear power plants would be available. In this same connection, the installation in structures of devices for measuring relative displacements during strong earthquakes has interesting possibilities. Such an idea was successfully used in a 43-story building in Mexico City, and gave a very useful record during the 1957 earthquake there. This principle has not been applied in any significant degree in the United States.

Another type of dynamic testing which has given useful results is the measurement of the period of the small vibrations set up in structures by wind, traffic, installed machinery, or microseismic activity. Existing commercially available seismographs are not well adapted to this purpose, but some special tests at the California Institute of Technology have shown that it should be possible to modify standard instruments to make them suitable for such tests. A comparison of the fundamental natural period of vibration of a structure as measured during a wind-excited vibration test with theoretical calculations will reveal something of the extent to which the basic dynamic behavior of the structure is described by the simplified models required by a mathematical analysis.

It has been proposed that vibration measurements of building periods before and after a strong earthquake might reveal significant structural changes, should they occur. It would thus be highly desirable to obtain period readings on existing nuclear power plant installations so that a basis of comparison would be available if a strong earthquake should occur.

7. Summary of Some Specific Research Projects in Earthquake Engineering for Nuclear Power Plants.

The foregoing general considerations on research in earthquake engineering have, of necessity, been put in rather general terms. The following section summarizes from the above background information a number of more specific research projects closely related to aspects of earthquake engineering that may be expected to be of direct interest to the nuclear power industry in the near future. These research projects are of a fundamental type, aimed at developing the basic information underlying the field. This does not preclude ad hoc research projects aimed at solving very specific practical problems. The following specific items will indicate the scope of a suggested program of research in earthquake engineering over the next five years.

(1) A set of six intermediate magnification short-period seismographs should be available for temporary field installation for 3-6 months at a site, and should be used for studies of detailed local seismicity and the effects of local geology and soil conditions on earthquake ground motions at sites of potential interest to the nuclear power industry.

(2) An improved strong-motion accelerograph suitable for measurements of ground motion and building response caused by strong earthquakes should be developed, and arrangements for commercial availability should be made. With this instrument, two programs of major importance should be carried forward: (a) additional accelerographs for recording ground motion during strong earthquakes should be installed at existing nuclear installations, and at sites in seismic regions of potential interest to the nuclear power industry; (b) accelerographs should be located at strategic points in buildings and special structures to record structural response to strong earthquakes.

(3) A continuing program should be established to exploit the possibilities of quarry blasts and nuclear bomb tests for ground motion studies and for structural dynamic tests. Contacts should be maintained with commercial quarry operators and with the Atomic Energy Commission to keep track of planned tests and provisions should be made for available personnel, instrumentation, and analysis of results.

(4) Basic studies in soil dynamics should be expanded, and the properties of typical soils under dynamic conditions similar to those encountered in strong earthquakes should be determined. Such questions as consolidation and liquefaction of soils under oscillatory forces require much more extensive investigation, both theoretically and experimentally.

(5) A catalog should be prepared, giving for all recorded strong-motion earthquakes, foreign as well as U.S., the recorded accelerograms, the calculated velocity and displacement time records, and the response spectrum curves. Much of this information is scattered throughout an

extensive literature and some of the necessary analysis has not been made. Such a catalog should be organized on a continuing basis so that it can be kept up to date. For some of the applications of importance in nuclear power plants, such as the seismic behavior of fluids in tanks, it is required that the earthquake response spectrum calculations be extended to longer periods than has been usual in the past. Such extensions of response spectrum data should be incorporated in the above catalog.

(6) The program of sinusoidal resonance vibration testing of full-scale structures should be much expanded. Such tests should be extended to yield conditions and to the point of failure. Some special test structures will be needed for this purpose in view of the damage which may be involved. Studies of the possibilities of large scale models for such nonlinear and failure situations should be pursued.

(7) Experimental and theoretical studies should be made of the dynamic characteristics of common structural elements and components. Studies should also be made of the dynamic characteristics of equipment special to nuclear reactor power generators, such as control rods, cooling systems, etc.

(8) In order to discover valid simplifications suitable for design of earthquake-resistant structure of all kinds, a program of comparison of accurate detailed calculations of structural dynamic behavior made with modern high speed computer techniques with various approximate solutions is needed. Components such as piping systems, containment vessels, control rod assemblies, etc. will all require study from this point of view if the results of research are to be made available in a

useful way to design engineers.

(9) The problems and implications of "seismic scram" should be studied to evaluate the conditions under which such a system might be advantageous.

The foregoing discussion should not be taken to imply that it is not possible at present to design nuclear power generators, or other structures, to be safe against earthquakes. Safe designs can be made, but they result in more cost than would be the case if more precise information on earthquakes and structural dynamics were available. Past studies of destructive earthquakes and of earthquake-resistant design were made with the design of ordinary buildings in mind. With the advent of the nuclear power generator it becomes economically desirable to have a much more accurate knowledge of earthquakes and their effects than had been considered necessary in the past. This requires that additional research be done to bring the state of knowledge to the desired level, and it is hoped that the above discussion will point the way towards increased progress in this important field.