THE STATE-OF-THE-ART FOR SEISMIC DESIGN OF NUCLEAR POWER PLANTS—AN ASSESSMENT

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SUMMARY

A new assessment of the state-of-the-art of seismic design of nuclear power plants has appeared necessary for several reasons. They include: (1) the nuclear industry's continuing concern for public safety; (2) a concern for the potentially-unnecessary public cost burden associated with excessive design conservatism; (3) the rapid development of seismic analysis and design methodology and changes in the technology; (4) the critical nature of seismic design as the limiting constraint in the siting of nuclear power plants in many parts of the world.

For these reasons, Applied Nucleonics Company (ANC) has recently completed an independent assessment of the state-of-the-art of seismic design. This work has been based on the experience of ANC personnel in this field as well as the efforts of many specialists from industry and government. Besides the state-of-the-art evaluation, ANC has delineated areas of research in seismic design and analysis which require further work.

Three general areas were investigated: soils, siting and seismic ground motion specification; soil-structure interaction; and the response of major nuclear power plant structures and components. In addition, a sample of industry experts was polled in an effort to establish industry concerns.

Major findings include the necessity of improving knowledge of seismicity and soil dynamic parameters; improved specification of seismic inputs used for design (the Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE)) and validation of models and methods used for soil-structure interaction calculations. Also considered important are the acquisition of additional experimental and test data on equipment and structures; certain changes to Regulations and Standards; and the development of simplified design methods suitable for industry-wide application.

Substantial conservatism in seismic design appears to be present in many areas; in others, the reliability and uncertainty of the design needs quantification. There is industry concern for the lack of skilled manpower with seismic design experience. Among the respondents to the questionnaire, there was nearly unanimous agreement as to the urgent need for preselected, preapproved sites with preestablished seismic design criteria for nuclear power plants. Furthermore, the role of the licensing and regulatory agencies has been questioned. At least in the United States, it appears that more emphasis should be placed on licensing and regulation and less on attempts to tell the industry what methods should be used for design and analysis.

The quantity of experimental data existing in the world today—from both tests and actual earthquakes—is so small as to be cause for concern. Additional work in this area is urgently needed, particularly on full-scale structures and at high levels of response.

1. Introduction

This report describes a review and evaluation of the analysis methods, design methods, and design standards used in the seismic design of nuclear power plants [1]. Three general areas were investigated: 1.) soils, siting, and seismic ground motion specification; 2.) soil-structure interaction; and 3.) the response of major nuclear power plant structures and components. In addition, a sample of industry experts was polled in an effort to establish industry concerns and areas which should be stressed in future research.

Three methods were used to carry out the research described in this report. The first involved experience in the analysis and testing of nuclear power plants and their structures and equipment. This includes analysis and experimentation conducted at power plants representing major types currently under construction both in the United States and abroad. Included in this experience, in addition to the questions of analysis, design, and measurement of dynamic parameters, are related efforts involving a review of responses obtained during measured earthquakes as well as investigations into methods and approaches suitable for backfitting or upgrading older plants to meet new seismic design requirements.

The second method involved a review of the available literature. In addition to technical reports and publications, other pertinent literature was examined. These studies have included international sources where applicable.

The third approach was to obtain opinions and recommendations from the U.S. nuclear power industry. This included contact with architect-engineering firms, consulting firms, public and private utilities both on the East coast and West coast, regulatory and licensing bodies, and Federal and State agencies.

2. Seismic Design Standards

An examination of current standards indicates in theory a reasonably clear division of the design process between the U.S. Nuclear Regulatory Commission (NRC) and the various design disciplines. In general, the NRC limits its guidelines for seismic design to the determination of the design seismic input, seismic monitoring of the completed power plant, and procedures for inspection of the plant in the event the design accelerations are exceeded. The design standards of the various disciplines in turn do not deal with the determination of the seismic input, but only present criteria to translate the calculated stresses into design numbers.

In U.S. practice, however, the division between the Regulatory Body(NRC) and industry (the design and manufacturing groups) is not so clear. The NRC has placed staff members on the various industry committees formulating standards and these members can have a disproportionate influence in some cases. While the NRC goal is undoubtedly to encourage the establishment of stringent standards to protect public safety, in some instances, excessive concern for regulatory policies and precedents has taken priority over the technical accuracy and completeness of the standard.

Industry may also be accused of proceeding slowly with the standards-making process. In some cases, the rigor of the standards has been influenced by geographical considerations. A utility executive in Maine, for example, does not approach a seismic standard with the same objectives as one from California. The inclination of industry to establish minimum standards has also been observed. In some areas, this approach may be justified, but instances are known where this approach resulted from the feeling that "whatever we do, it will be increased, so let's go in low."

In developing standards, it is important to bear in mind what constitutes a "failure" in a nuclear power system subjected to earthquake forces. The ultimate goal is protection of the public against radiation releases. Towards this purpose, the complete collapse of certain auxiliary buildings may be unimportant, while a small crack in a critical pipe or in the containment system could be disastrous. The main constraint in safety-related structures and equipment in nuclear power facilities is that they are capable of performing their safety function following an earthquake. This results in unique considerations which impose different limitations on design standards, and particularly on standards for qualifying equipment.

Another area which has been inadequately addressed by present standards is methods for combining loads used in design. These methods must consider normal operations, abnormal operation, emergency conditions, and potential accident conditions. There is no uniform treatment of these various conditions in seismic design, but the tendency is toward designing for the case of combined loads, simultaneously applied. This approach may lead to conservative designs.

On the other hand, if normal operations (with a probability of occurrence of 1.0) and an accident condition (such as an earthquake having a probability of 10^{-4} to 10^{-6}) produce equal loads, they should not be evaluated equally. There is danger that concern for the improbable event might detract engineering judgement and attention from the certain event, resulting in a less adequate design.

A point of concern may be raised relating to the degree of accuracy that can be obtained if components designed by different disciplines using different design standards are dynamically coupled to a high degree. Because design is an iterative procedure, this would require the interaction between designers of different disciplines and possibly of different companies. A possible solution would be the approach of performing a final dynamic analysis after the completion of the total design to insure that the coupled components were not designed in a manner that under dynamic loading would provide for unfavorable interaction.

To summarize, preliminary steps have been taken in the development of seismic design codes and standards. These standards, including the U.S. NRC Regulatory Guides, vary in quality and appropriateness as might be expected at this point in time in the nuclear power industry. Further work should be done, particularly to improve ANSI N41.7 (IEEE-344) and also to draft a new standard for seismic qualification of mechanical equipment.

3. Seismic Design Methods

The seismic design of nuclear power plants is by nature an iterative process, one which could be called "design by analysis." Thus, reliability of the design depends both on the adequacy of the analysis which is used to predict loads and stresses and on the knowledge of the properties and characteristics to resist these loads and stresses. Procedures and methods used for design as well as the acceptable loads for different types of structures and equipment are spelled out by industry and government-established standards, and regulations discussed above. There is a greater diversity in the methods of analysis. These methods are discussed more fully in Section 4.

Figure I shows the estimated engineering man-hours for the design of a current generation nuclear power plant compared to a plant designed five years ago. It is apparent that there has been a significant escalation of the design effort, particularly in the design of mechanical components. Part of this can be attributed to larger plants but much of it is due to the increased complexity of the design process and licensing requirements.

Based on a review of present design methods, it appears that there is a great deal of conservatism in the seismic design of nuclear power plants. It has been said that the margin of conservatism in a nuclear power plant is ten to 50 times greater than in a conventional steel-frame high-rise building [2]. This conservatism arises from the redundant safety factors which are applied first to the soil parameters and the seismic inputs, secondly to the calculation of structural responses, and finally to the approaches used in the design and testing of equipment. A factor of conservatism applied to the input motion which drives the containment building is thereafter multiplied as the energy excites the building because of the amplification produced by the building. In addition, other factors of safety are applied in calculating the response of individual items of equipment and each conservatism adds to the previous ones. Certainly some degree of conservatism is necessary to compensate for our imperfect knowledge of how large structures respond during strong motion earthquakes. But we pay a high price for the conservatism in current designs, and a better approach would be to establish the degree of conservatism needed in the design of plants and to have that degree and no more or no less.

Critical areas in the design process are the design of structures, equipment and equipment supports, and piping systems. Of these, equipment supports and piping systems are probably the most important. The design of large massive equipment is next in importance while other types, particularly those which are light in mass or extremely rigid, is less critical. The design of structures is important and requires careful attention to details but the seismic loads are not generally the limiting criterion for the stresses in the structure.

4. Analytical Methods

4.1 Soils, Siting, and Soil-Structure Interaction

In the estimation of site and free field responses to earthquakes, the lack of strong motion data is a major problem. In some regions, historical earthquakes are either nonexistent or not easily related to surface faulting. Another critical area is that of improving knowledge of *in situ* soil parameters at high strain levels.

The soil-structure interaction problem is also an important area in the seismic design of nuclear power plants. It involves the process of extensive computations which are frequently expensive and are based on parameters known with limited accuracy. Nonlinear effects appear to be extremely important but are currently treated in only a very approximate manner, if included at all.

Experimental tests using semi-scale and if possible full-scale structures should be conducted to study both nonlinear soil effects and to check on the existence and significance of the "driving" effect of side soil. The results of a test program should be compared to response predictions of alternative nonlinear models using available numerical methods to establish method suitability and perform parameter studies. The purpose of such work would be to (1) develop approximate analytical methods and guidelines suitable for the design and analysis of massive structures for a range of site, structure and excitation conditions and (2) identify those conditions for which a more rigorous analysis is necessary using verified nonlinear analytical procedures. Emphasis should be placed on methods of obtaining and incorporating more accurate soil parameters and design guidelines should be developed to assist the analyst in adequately modeling soil effects on key structures without requiring large technical resource commitments for every site and structure.

4.2 Reactor Building Response

The structural analysis of nuclear reactor building response to earthquakes is clearly a complicated endeavor involving many assumptions and uncertainties. With proper detailing and attention, reactor buildings probably can be designed to resist seismic forces in excess of those anticipated anywhere in the world [3]. The main significance of the building analysis is then to provide dynamic inputs to the internal equipment which is usually more difficult to design to withstand seismic forces.

Nevertheless, there are some areas that require further development. Most current building models assume that the containment base mat is rigidly rocking and translating on the soil. Experimental evidence indicates that the base mat flexes during seismic excitation. Studies should be made to evaluate the significance of this effect.

Several areas will involve future changes in the state-of-the-art. The nonlinear response of the containment, especially with respect to damping, requires further study. The sensitivity of response to damping variations and the actual damping found in structures must be reviewed. The method in which response from different modes and from inputs from different directions are combined will continue to be discussed. Similarly, methods of generating response spectra are still being refined. The use of finite element methods will become more popular. We must not assume that this method is automatically better than existing methods. The use of any new approach must be fairly compared with earlier methods and against experimental data. The use of shell models may also become more prevalent.

Additional testing of model and full scale structures with intent to provide data for model and parameter verification is required. High-level tests and tests compared with predicted model responses would be useful. Experience with actual earthquakes will be valuable.

The question of ground rupture, the degree of complexity of the lumped parameter model and the methods used in detailed analyses must be reviewed.

Finally, the uncertainties and conservatisms in reactor plant design must be quantified. The uncertainties come not only from varying material properties but also from variation of construction methods and errors in analysis method. A recent study of two nuclear power plant containment buildings and equipment indicated that 20% of a randomly-selected set of structures had not been adequately analyzed to demonstrate seismic capability [4]. Certainly the best of available analysis procedures are useless if they are not applied properly.

4.3 Equipment Response

The seismic design of equipment and piping systems for nuclear power plants is a critical safety-related function. Sophisticated methods are available for the analysis of both equipment and piping systems and many engineering man-hours and much money is spent on this in each nuclear power plant design. Although the mathematical methods used in this process are in themselves often adequate, the results obtained are spotty because of inadequacies in applying the methods and in modeling the supports which are extremely important to the response of the equipment. Furthermore, an additional deficiency arises from the lack of adequate data concerning the nonlinear properties of materials and damping values suitable for use at high response levels characteristic of strong motion earthquakes.

One solution is to perform extensive proof testing of all equipment but this is both expensive and impractical considering the heavy equipment installed in nuclear power plants. Furthermore, laboratory proof testing leads to additional discrepancies and is not always adequate. Thus, it is necessary to develop analytical methods which employ the available theory and yet yield consistent and accurate results. Improvement could result both from improved data to use in the analyses and a requirement to check out analytical methods and results on equipment installed in existing structures. Improvement in this area should come automatically as additional test data become available.

4.4 Seismic Instrumentation and Real Time Monitoring for Damage Assessment

It is within the current state of the art to measure both ground acceleration and structural accelerations during earthquakes. These values can then be compared with the values used in the design of a power plant, to verify plant safety following an earthquake, to establish the need for shutdown, and to verify the validity of the original analysis and design. Two documents with different and somewhat conflicting requirements govern seismic instrumentation in nuclear power plants. The industry-prepared ANSI 18.5 establishes a basic set of instrumentation and recommendations. The NRC Regulatory Guide 1.12 references ANSI 18.5 but imposes additional instrumentation requirements, modifies the locations, and changes the conditions under which additional instrumentation is required.

Perhaps the seismic instrumentation ought to really be measuring the parameters (stresses, forces, shears, displacements, strains) which are used in the design of the plant, rather than acceleration, which for historical reasons was first used by seismologists in their study of the earth's motion during earthquakes.

Another major problem is the role of seismic instrumentation relative to shutdown criteria, real time monitoring, and rapid damage assessment. It is the intent of the regulations that a power plant should be shut down if the OBE is exceeded until it can be demonstrated that the plant can be operated with complete regard for public safety. This leads to the possible usefulness of advanced seismic analysis systems capable of real time analysis, and to automatic shutdown systems. The primary concern should be to develop systems that minimize societal risk from both unnecessary shutdowns of safe plants and unwise operation of damaged plants.

5. Limitations of Available Data

Experimental data on the dynamic response of nuclear power plant structures and equipment to moderate (>0.15 g) levels of seismic excitation are not currently available. Indeed, until the 1971 San Fernando, California earthquake, structural response recordings for any type of structure were very few in number. However, data collected by a variety of vibration testing techniques indicate that currently accepted analytical procedures, even when correctly applied, have significant limitations. These limitations are pronounced in the area of soil dynamics and soil-structure interaction (due in part to nonlinear phenomena) and in nonlinear response of some structures and equipment.

Limited experimental investigations indicate that nonlinear behavior may certainly be important in some structural systems, and limited numerical experiments indicate that nonlinear phenomena may result in either conservative or unconservative designs, depending upon opposing influences.

Observed errors in the analysis of systems using linear methods remind one of the human element since seismic analysis involves both art and science. Such errors and uncertainties in materials, construction, and installation attest to the importance of dynamic testing of important structures composing nuclear power plants.

6. Findings

6.1 Comparison of Theoretical and Experimental Values

As discussed above, there exist virtually no data on the response of nuclear power plants to even modest ground excitation. Limited dynamic response data do exist as a result of various dynamic tests conducted during the past seven years at nuclear power stations, but are generally limited to low response levels for both equipment and structures.

Currently available comparisons between analytical dynamic response predictions and the experimentally determined reality are quite limited. The preponderance of comparisons apply to semi-scale models of equipment or structures (particularly for studies in soil-structure interaction).

As might be expected, comparisons between experiment and analysis present examples of both good and poor correlation. The correlation quality is in part a function of the particular analyst and assumptions employed in reducing large degree-of-freedom problems to their essentials. The quality also is a function of analytical tools generally available to the engineer and the fundamental limitations of alternative approaches.

The nonlinear response characteristics of soils, structures, and equipment present a major source of potential error when using currently accepted analytical approaches (linear models). Nonlinear effects may result in either conservative or unconservative designs, depending upon the magnitude of various phenomena. Experimental evidence of nonlinear dynamic behavior exists for both soil-structure systems and for equipment; however, data and analytical comparison are quite limited and inconclusive.

6.2 Potential for Damage Prediction

Significant damage to critical structures and critical internal equipment (pressure boundaries) fabricated with the materials conventionally employed implies nonlinear dynamic response. Expected response nonlinearities arise from both large displacements affecting structural system geometry and from inelastic and plastic material behavior. While prediction of damage thresholds may be based in principle on linear elastic models (depending upon the level of geometric distortion under dynamic load), prediction of the degree of system damage and remaining margin to failure must be based on nonlinear analytical procedures.

The ability to adequately predict degree of damage in special structures appears to be within the means of current or near term analytical capabilities. Efforts to refine existing analytical capability and develop additional capability should be supported by the nuclear power industry. It is vital that parallel experimental programs be supported to verify the accuracy of analytical tools. Such verified analytical capabilities could be extremely useful in determining remaining capacity of a nuclear power plant subjected to damaging seismic excitation, minimizing the time that will almost certainly be required for plant recertification following a significant earthquake.

6.3 Other Findings

Major findings include the necessity of improving knowledge of seismicity and soil dynamic parameters; improved specification of seismic inputs used for design (the SSE and OBE), and validation of models and methods used for soil-structure interaction calculations. Also considered important are the acquisition of additional experimental and test data on equipment and structures; certain changes to Regulations and Standards; and the development of simplified design methods suitable for industry-wide application.

Substantial conservatism in seismic designs appears to be present in many areas; in others the reliability and uncertainty of data need quantification. There is industry concern for the lack of skilled manpower with seismic design experience. Among the respondents to a questionnaire, there was nearly unanimous agreement as to the urgent need for preselected, preapproved sites with preestablished seismic design criteria for nuclear power plants. The role of the Nuclear Regulatory Commission (NRC) has been questioned; more emphasis should be placed on licensing and regulation, and less on establishing acceptability of design and analysis methods.

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FIGURE I

REVIEW OF NUCLEAR PLANT DESIGN PARAMETERS