SEISMIC DESIGN OF NONREACTOR NUCLEAR FACILITIES[i]

by

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SUMMARY

In this paper, the state-of-the-art for seismic design of nonreactor nuclear facilities is discussed. The paper focuses on both safety and economic aspects and primarily reflects trends of uranium enrichment plants.

INTRODUCTION

General. The development of earthquake engineering technology has increased considerably over the past two decades because of the needs to provide safe nuclear power plants and safe building structures. These needs represent the ends of a spectrum. The upper end, related to power plants, requires rigorous seismic design criteria and must be approved by the Nuclear Regulatory Commission (NRC) in the United States (1). The lower end of the spectrum requires less rigid criteria as specified by a building code (2). Seismic design requirements for nonreactor nuclear facilities should fall somewhere between these two ends.

Nonreactor Nuclear Facilities. Nonreactor nuclear facilities include, but are not limited to, uranium enrichment plants, fuel reprocessing plants, experimental test facilities, and waste storage facilities. The guidelines discussed herein can also be applied to nonnuclear facilities. For example, toxic chemical plants are very similar to uranium enrichment plants; i.e., their potential for hazardous exposures to the public or the environment are of the same order of magnitude.

Nonreactor nuclear facilities now in operation were designed to different safety and economic standards than if they were to be built today. Some are being expanded to support the world's increasing demand. It is important that these facilities be reviewed and that engineers, scientists, and managers address such concerns with the appropriate perspective towards establishing safe and cost-effective facilities.

DETERMINING THE EARTHQUAKE ENVIRONMENT

Background. Designing a facility is probabilistic in nature even though, in most cases, a deterministic approach is taken. Because of the lack of understanding of the earthquake phenomena, the infrequent occurrence of such

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events, and the safety and economic importance of nonreactor nuclear facilities the establishment of a site's earthquake environment should be considered from a probabilistic viewpoint.

Current Methodology. A number of probabilistic methods have been developed and studied. The culmination of these works has resulted in a viable methodology that has five key characteristics: 1) developing seismic source regions based on historical earthquake activity, and geologic and tectonic characteristics, 2) establish a recurrence relationship -- a bayesian poisson process, 3) determine epicentral intensity and magnitude relationships, 4) determine site intensity and peak ground acceleration relationships, and 5) establish attenuation relationships. This methodology provides a good estimate when verified with deterministic evaluations, is a straightforward approach, and when properly presented it is better understood by the decision makers (managers) -- a very important aspect.

Annual Hazard Curves. It is recommended that the seismic risk at a site of a nonreactor nuclear facility be defined in the form of curves relating return period to peak acceleration (annual hazard). The peak accelerations for such curves usually represent the free-field peak horizontal ground accelerations for an average site condition (a fact that is often not made clear in risk studies). Caution must be used in developing such curves to avoid conservatism being piled on top of conservatism. The mean and one standard deviation curves should be shown.

ESTABLISHING SEISMIC DESIGN LEVELS

Independence of Facility. The advantage of establishing a site's earthquake environment using the methodology discussed above is that it is totally independent of the type of facility being considered. However, care must be exercised to assure that the proper safety and economic importance of such studies are established.

Management Decisions. Having established an annual hazard curve for a site the appropriate seismic design levels may be selected. It is important for the engineer and the scientist to explain the seismic risk to the managers so that they understand and can make effective and timely decisions from both safety and economic viewpoints. (In many large projects the seismic risk may be of minor concern to the managers when looking at all the problems that can occur with managing large projects.) Once such decisions have been made they represent a part of the overall risks management and the public are willing to accept. Management accepts these risks by establishing the seismic design levels through the seismic design criteria, and the public accepts these risks by approvals through a public review system.

Dual Level Earthquakes. The philosophy that has developed over the years in the U. S. is that facilities such as power plants and enrichment plants should be designed for two levels of earthquakes. The first level represents that peak acceleration that is likely to occur at the site sometime during the life of the facility. The second level represents that peak acceleration that is believed to represent the maximum level that the facility should be designed for when primarily considering the aspects of safety. In the case of nuclear power plants (1), these two earthquakes are defined as the Operating Basis Earthquake (OBE) and the Safe Shutdown Earthquake (SSE), respectively. For the Trans-Alaska Pipeline Project (3), " a nonnuclear facility", the two levels of earthquakes were defined as the Design Operating Earthquake and the Design Contingency Earthquake. Earthquake levels recommended for enrichment plants have been called the Operating Earthquake (OE) and the Maximum Earthquake (ME).

In most cases, facilities are designed to continue operating during and/or after the lower level earthquake excitation occurs. However, for the higher level earthquake, the facilities are designed to maintain a safe condition with a lesser regard for the economic aspects. In the case of facilities where continued operation is not of major concern, the dual level approach may not be appropriate.

Choosing Levels. The particular OE and ME chosen from the annual hazard curve depends entirely upon the facility under consideration. In the past, in the U. S. the OE has been chosen to be one having a return period of 70 to 200 or 300 years while the ME return period may range anywhere from 600 to 10,000 years. For the Tennessee Valley Authority's Phipps Bend nuclear power plant, the OBE return period was determined to be between 390 and 740 years (4). The SSE return period was determined to be approximately 20,000 years (5). For some enrichment plants the OE return period has been recommended to be 72 years while the ME return period has been recommended to be 1,000 years. For most nonreactor nuclear facilities, a return period for an OE should be in the range of 70 to 200 years, while the ME should be in the 500 to 1,000 year range. Having chosen acceleration levels other important seismic inputs may be estimated (i.e., velocity, displacement, duration, etc).

ECONOMICS AND SAFETY

Economics. The economic decisions discussed in the previous section are made by the facility managers after considering capital investment, cost of repair, impact of nonoperation, ownership, investors or taxpayers, and users. There are no specific guidelines that managers must follow in making their economic decisions. However, to assure certain decisions are made concerning safety, various governmental agencies have imposed safety requirements on most facilities in the U. S.

Safety. The U. S. Department of Energy (DOE) has established safety requirements for nonreactor nuclear facilities -- Order 5481.1 (6). The general purpose of this order is to assure: 1) identifiable risks no greater than those for comparable licensed nuclear facilities, 2) no undue risk to the health and safety of the public and employees, and 3) protection of property and the environment from identifiable undue risk. To verify that such requirements are met, certain documentation must be prepared: 1) Safety Assessment Documents (SAD) to identify hazards and safety requirements of a facility; 2) if the SAD identifies nonindustrial safety hazards, a Preliminary Safety Analysis Report (PSAR) is required for planned facilities; 3) following the PSAR a Safety Analysis Report (SAR) is required for the DOE approval; and 4) Operations Safety Requirements (OSR) must be identified. Thus, the risk assessment efforts for nonreactor nuclear facilities are similar to those for nuclear power plants, the difference being in the potential risks -- generally lesser to varying degrees for nonreactor nuclear facilities.

CLASSIFICATION OF STRUCTURES, SYSTEMS, AND COMPONENTS

General. For nonreactor nuclear facilities and major nonreactor facilities[1] it is recommended that classifying structures, systems, and components be done using a systems approach. This approach will allow for proper consideration of all aspects of the facility, safety, and economics, and can result in one classification system for not only seismic safety but operational reliability and operational safety as well. Identifying the structures, systems, and components that fit into various classes should be assisted by decision-tree analysis, fault-tree analysis, failure modes and effects analysis, and PSARs.

Specific Cases. For one enrichment plant four classes have been proposed, each based on a fault-tree termination point: Class I -- no personal injury or total cost less than $5,000; Class II -- minor injury or occupational illness or total cost between $5,000 and $500,000; Class III -- major injury or occupational illness or total cost between $500,000 and $5,000,000; and Class IV -- multiple, major injuries or occupational illness or fatality or total cost greater than $5,000,000.

For the Trans-Alaska Pipeline Project (3), the above systems approach to classification was not used. However, a practical approach was taken which was based on considerations for seismic design to provide safety of the environment, and to provide a cost-effective project.

ESTABLISHING ANALYTICAL REQUIREMENTS

Building Codes. When specifying the use of a building code for a nonreactor nuclear facility, or any similar facility, it must be remembered that a building code is just that -- a building code. In many cases, e.g., process piping, the building code does not apply. Therefore, when specifying seismic design criteria for such facilities care should be taken -- specifying "where the building code does not apply, good engineering judgment should be used" is generally not satisfactory.

Response Spectra. The response spectrum, modal analysis technique is generally used for providing the required design assurance of Class III and Class IV type structures, systems, and components. At present it seems reasonable that for nonreactor nuclear facilities the horizontal seismic input should be based on using the horizontal spectra shape of RG 1.60 (7) for both rock and average soil sites. The vertical seismic input should be taken as two-thirds the horizontal. Where unusual soil sites are encountered there may be justification for site-dependent spectra. The overall importance of the facility should have a major impact on such justification. Some reasoning for recommending RG 1.60 is: 1) a nonreactor nuclear facility is a nuclear facility and if licensing is required RG 1.60 is readily acceptable; 2) a considerable amount of effort has gone into developing the spectra shapes; 3) more recent works have not shown RG 1.60 to be too conservative or nonconservative; and 4) recent work has shown the two-thirds criteria to be conservative. If licensing is not an issue the spectra shapes in NUREG 0098 (8) may be more appropriate.

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[1] The Uniform Building Code (2) has identified classification systems for conventional buildings.

Site-Dependent Spectra. By making the above recommendations it is not the intent to suppress the use of site-dependent spectra. In fact, the seismic design criteria for one enrichment plant used RG 1.60 spectra shapes when designing the balance of plant to meet the safety requirements of Order 5481.1, and site-dependent spectra shapes for the design of specific seismic sensitive equipment. In this case, it was judged that RG 1.60 was too conservative from an economic viewpoint.

Time-Histories. Standard practice has been to develop one time-history whose response spectra generally envelops the design spectra shape. However, multiple time-histories (four or five) may be desirable for consideration of phasing relationships and differences in frequency content. It is imperative that time-histories represent the type of earthquake motion that might occur at the site and care should be exercised when developing artifical time-histories. It is recommended that actual records (if available) from similar sites and resulting sources be modified to envelop the design spectra.

Mathematical Models. Mathematical models must adequately represent the physical characteristics of the particular structures, systems, and components and their response to seismic excitations. Soil-structure interaction and the effects of torsion caused by traveling waves should be considered. When combining modes the method of the square root of the sum of the squares is quite appropriate. However, care should be exercised with closely spaced modes and acceptable methods have been specified (9). For large structures, systems, and components uncoupling may be an option to simplify the models. Studies have been conducted on uncoupling effects and recommendations have been made (9) and should be used for nonreactor nuclear facilities. The relative displacements between models must be examined, and where predominant frequencies are below 0.5Hz, displacements may be the controlling factor in design. All analyses should be conducted in the two orthogonal horizontal axes and the vertical axis that coincide with the principal axis. When the analyses are performed independently in each direction, the resulting displacements, moments, etc for the final results shall be computed as previously recommended (10) For structures, systems, or components supported at multiple points by different structures, the support point spectra should be superimposed with the design support spectra becoming the upper bound envelop.

Damping. The RG 1.61 (11) recommends damping values and a discussion on the subject has been presented (10). For most nonreactor nuclear facilities, the upper values presented in Ref. 10 should be quite satisfactory.

Simplified Analysis. The analysis of a Class III or Class IV type structure, system, or component may be conducted using a conservative simplified approach. During the design phase of a facility, a simplified approach may be necessary where long lead times are required for the design and procurement, and very little, if anything, is known about the supporting structures. The RDT (9) has recommended acceptable simplified procedures.

Inelastic Analysis. When designing nonreactor nuclear facilities every opportunity should be taken to design in the inelastic range since this area is where a structure absorbs the larger portion of earthquake energy. To conduct inelastic analysis, the modification procedures of the elastic spectra previously recommended (e.g., Ref. 12) should be used. Ductility values to be used for inelastic design have been recommended (e.g., Ref. 12). Extreme care must be taken in the design and construction to assure that the intended ductility is in the actual structure.

ESTABLISHING DESIGN REQUIREMENTS

General. When developing seismic design criteria, it is important that emphasis be placed on the design requirements. Many seismic failures have been attributed to the lack of design detail.

Load Combinations. A number of load combinations have been proposed in the literature. For some enrichment plants, the load combinations specified in ANSI A58.1 (13) have been used. However, the use of the probability factors specified in ANSI A58.1 may not be appropriate for all nonreactor nuclear facilities. A realistic assessment of the actual loads that could occur on a structure, system, or component should be conducted.

Stresses. The allowable stresses will vary depending on the classification; type of structure, system, or component; and level of safety and economic importance within a class. For example, when designing for an OE the stresses caused by normal operating loads and the seismic loads should remain within the normal allowable working stresses. For the ME inelastic design may be used as long as the specified ductility values are not exceeded. For Class III and Class IV type structures, systems, and components that are primary toxic or nuclear containment systems, consideration should be given to not allowing the stresses to exceed 90 percent of the materials general yeild stress during a ME.

Site Considerations. If potential surface faulting or liquefaction exist at the site, the foundation design must take this into consideration. However, the site should be selected where such potential does not exist. To determine the soil seismic characteristics at a site, vibro-seismic studies should be conducted.

Piping. Where special considerations must be given above and beyond piping codes they shall be spelled out in the seismic design criteria. In may cases, it may be desirable to design piping interfaces between two structural units as a de-coupled system. Special consideration must also be given to buried piping. Abrupt changes in stiffness at locations, such as building entrance points, valve blocks, and similar restraints, serve as special hazard/failure points.

Other Considerations. During design other consideration must be given to structures, systems, and components that might not normally occur unless specified. Support systems, bracing, etc for heat and ventilating equipment tanks, etc must be seismically designed. Suspended systems such as light fixtures must be properly braced. Cranes should also be designed to remain on their rails during an ME although they may not be required to function following the ME.

TESTING OF STRUCTURES, SYSTEMS, AND COMPONENTS

General. In many cases, particular structures, systems, and components are difficult to analyze to show they will perform as intended. This generally occurs with mechanical and electrical equipment, and such instances may require testing.

Qualification. IEEE-344 (14) has been written for testing electrical equipment that must be qualified for nuclear power plants. For nonreactor nuclear facilities, IEEE-344 is quite appropriate to use as a guide for qualifying Class III and Class IV type equipment. However, in many cases, a more relaxed qualification procedure should be followed (3).

PRACTICAL ASPECTS

Systems Engineering. From a systems point of view it is important that managers, all design disciplines and procurement groups be involved in the seismic design process from the beginning. The numbers of different structures, systems, and components for any large facility can be astronomical and a concerted effort by all involved is required.

Seismic Design Criteria. The design requirements discussed in the previous sections can be used as a guide for developing seismic design criteria for nonreactor nuclear facilities. When developing specific criteria, it should not become so rigid that it does not permit the use of alternate methods where justifiable.

Seismic Input. Although specific recommendations have been made engineers should not blindly use a response spectrum shape without due consideration of the seismic sources, the site, and the facility. Depending on the type of facility, the effects of long-period motion and/or traveling waves may be of significance.

Computer Codes. When using computer codes to predict response of structures, systems, or components care should be exercised to assure the results are indeed realistic. Methods for checking results must be established and maintained throughout the design phase of a project.

Seismic Design Management. Classification, analysis, design, and testing of all the structures, systems, and components of a facility is a monumental task and requires some form of a management system. To make things even more complex, a large project may have several architect-engineering firms involved, each with responsibility of certain portions of a project. To assure that coordination occurs and that the seismic design requirements are met, a Seismic Review Team (SRT) should be established. The SRT should have a major role in establishing classification of structures, systems, and components and qualification requirements.

EXISTING FACILITIES

General. When examining existing facilities it is usually determined that to upgrade a facility to prevent economic losses is not cost effective and safety then becomes the issue. However, a facility is not evaluated unless an SAD requires an SAR.

Evaluation. To conduct a seismic evaluation of an existing facility requires an effort similar to the requirements discussed in the previous sections for new facilities. If safety is the main concern in the evaluation only one earthquake level needs to be established -- the ME level. If a series of different facilities are being examined and if a number of different engineering consulting groups are doing the work it is important that standards of evaluation be set.

Management prefers quick turn-around on evaluation studies so that they can begin budgeting for the anticipated reconstruction work. To allow seismic evaluators to focus on the more important structures, systems, and components facility operators can prepare safety evaluation tables where structures, systems, and components are examined for potential failure modes and then the consequence of such failure identified. Preparation of safety evaluation tables is similar to the classification process for new facilities but has been found to be more effective for existing facilities. In the evaluation, every advantage should be taken to utilize the inelastic capacity of the facility.

Expansions. When an existing facility is being expanded, the expansion should be designed to the state-of-the-art. Where the expansion is dependent on the existing facility, management must weight the risks to evaluate the justification for upgrading the existing facility.

CONCLUSIONS

When conducting seismic design of new or existing nonreactor nuclear facilities or major nonnuclear facilities, the guidelines specified herein should be appropriate. It is important that each facility be evaluated from a systems viewpoint, considering the aspects of safety and economic importance, and that the scientists and engineers keep the managers properly informed so that effective and timely decisions can be made.

LIST OF REFERENCES

1. 10CFR, Part 100, "Reactor Site Criteria", Fed. Reg., Vol. 38, No. 318, November 1973
2. Intl. Conference of Building Officials, "Uniform Building Code", 1979 Ed.
3. Anderson, T. L., and Nyman, D. J., "Lifeline Engineering Approach to Seismic Qualification", Journal of the Technical Councils, ASCE, Vol. 105, No. TC1, Proc. Paper 14531, April 1979, pp 149-161
4. Tennessee Valley Authority, Phibbs Bend PSAR, 1975b
5. Private Communications with Joe E. Hunt, TVA, December 17, 1979
6. Order DOE 5481.1, "Safety Analysis and Review System", U.S. DOE, February 1979
7. U.S. AEC, "Design Response Spectra for Seismic Design of Nuclear Power Plants", Reg. Guide 1.60, October 1973
8. Newmark, N. M., and Hall, W. J., "Development of Criteria for Seismic Review of Selected Nuclear Power Plants", September 1977, Published as Report NUREG-CR 0098, U.S. Nuclear Regulatory Commission, 1978
9. U.S. Department of Energy, "Seismic Requirements for Design of Nuclear Power Plants and Test Facilities", RDT Std. No. RDT F9-2, January 1979
10. Newmark, N. M., and Hall, W. J., "Earthquake Resistant Design of Nuclear Power Plants", Article for Intergovernmental Conference on Assessment and Mitigation of Earthquake Risk, February 1976
11. U.S. AEC "Damping Values for Seismic Design of Nuclear Power Plants", Oct. 1973
12. Newmark, N. M., "A Response Spectrum Approach for Inelastic Seismic Design of Nuclear Reactor Facs.", Transactions Third Intl. Conf. on Stru. Mech. in Reactor Technology, Paper K5/1, London, England, 1975
13. American Natl Std." Bldg. Code Requirements for Minimum Design Loads in Bldgs. and Other Structures", ANSI A58.1 - 1972
14. IEEE Std. 344-1975, "IEEE Recommended Practices for Seismic Qualification of Class IE Equipment for Nuclear Power Generating Stations", January 1975