A Review of Potential Technology for the Seismic Characterization of Nuclear Energy Centers

by
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July 1977

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FOR THE SEISMIC CHARACTERIZATION
OF NUCLEAR ENERGY CENTERS

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1.0 INTRODUCTION

This study is part of the ERDA-funded Hanford Nuclear Energy Center (HNEC) Program and is one of a series of technical investigations in support of that study. The primary objectives of the study were: 1) to review, analyze, and summarize the existing seismic evaluation technique and criteria for the siting and design of individual nuclear facilities, 2) to speculate as to how the criteria may change in the immediate future, 3) to convey the concept that new seismic criteria may have to evolve in the future to accommodate the magnitude of capital, generating capacity, and nuclide inventory associated with the centralized NEC concept, and 4) to identify techniques and tools that may be available to guide in the drafting of and the compliance with any new seismic criteria.

Risk is often defined as the mathematical product of the occurrence probability of a specific event and the associated consequence. The consequences may be categorized as 1) primary, i.e., impact of a radioactive release to the biosphere, and 2) secondary, i.e., loss of electrical generating capacity. Assuming that all of the facilities within a NEC respond as a unit to an initiating (seismic) event, it would appear that the centralization concept would be at a disadvantage. The consequences of an event in excess of the Safe Shutdown Earthquake (SSE) or the Design Basis Earthquake (DBE) would be greater than for the dispersed siting concept. However, if all of the funds expended on the siting and seismic design for the dispersed concept were channeled into a single enhanced evaluation of the centralized site, then possibly the error band associated with the SSE and DBE events might be reduced. Furthermore, improved facility design might be implemented due to the more dramatic consequences associated with centralization. In other words, if all of the eggs are placed in a single basket, one would like to have the basket of strength commensurate with the consequences of losing the contents. The fundamental point is: the NEC concept may motivate technological advancements in seismically related design and siting of nuclear facilities and may prompt the evaluation of new criteria specifically designed to reduce the risk associated with the centralization concept.

2.0 PRESENT SEISMIC CRITERIA

The Nuclear Regulatory Commission (NRC) is charged with the responsibility for regulating all uses of nuclear energy. To fulfill this function, the NRC has established design requirements for nuclear power plants, and reviews each license application for construction of such a facility to ensure that these requirements are met.

Many factors are evaluated when designing nuclear plants in order to provide sufficient safety for operation, control, and containment. Of these factors, the resistance of a nuclear power plant to strong motion earthquakes is one of the most significant design constraints considered in a license application.

Earthquakes present a unique hazard because their potential effects on nuclear plants are among the most significant that can result from natural causes. They are also unique in that they simultaneously threaten every structure, system, and component, even redundant systems, and thus lead to the possibility of a common mode failure. In addition, the ground motion induced may result in associated phenomena, such as landslides, subsidence, or liquefaction of the soil in and around the plant site.

The design requirements are established via laws, regulations, and established policy. To provide an overview for site selection and design requirements arising from seismic and geologic considerations, an appendix to the NRC criteria, 10 CFR 100, title "Appendix A - Seismic and Geologic Siting Criteria for Nuclear Power Plants," has been formulated (AEC, 1975). This appendix is to be followed by all applicants for nuclear power plant construction and operating licenses. It contains seismological and geotechnical requirements and general procedures for determining seismic input criteria at a site. This includes consideration of potential earthquake-induced effects such as vibratory ground motions, soil and slope instabilities, floods, and water waves. These criteria must be incorporated in preliminary and final safety analysis reports, prepared according to standard NRC format and content requirements (AEC, 1972). In addition, the criteria must be

used in conjunction with NRC regulations which are issued as NRC Regulatory Guides. These guides establish those methods, techniques, and parameters that are acceptable for use in a license application. The NRC has also issued their Standard Review Plan (SRP) in an attempt to speed licensing time. This document describes in detail specifically how the NRC reviews a license application and the material the application is expected to contain. These various documents, many of which are summarized in Appendix A, provide the basis for this section.

The remainder of this section is organized into four subsections, each of which describe in more detail the present seismic design criteria for nuclear power plants. Seismic Input describes the methodology used to obtain site ground motion for design. As this is one of the most controversial elements of the design chain, considerable detail is presented. Soil-Structure Interaction describes methods used to quantify the effects of ground motion on site structures. Structural Analysis describes the methods used to analyze and design structures for the effects of earthquake ground motion. Seismic Operating Criteria describes various criteria affecting plant operation.

SEISMIC INPUT

The principal investigations and procedures required to license a nuclear plant are outlined in the NRC criteria document denoted as Appendix A, 10 CFR 100, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," (AEC, 1974). This section reviews the geologic, seismologic, and site soils investigations and testing required for use in deriving ground motion criteria in accordance with the above document.

In order to comply with Appendix A, 10 CFR 100, the coordinated efforts of the geology, seismology, and engineering disciplines are required (Figure 1).

The planning phase comprises the preliminary work required to develop and coordinate subsequent field and office studies. This includes literature reviews, site inspections, and scheduling of future work.

FIGURE 1. Geotechnical Investigations for Evaluating Ground-Motion Characteristics

The investigation phase includes detailed regional and site investigations, laboratory testing, and preliminary estimates of vibratory ground motions at the site. The work in each of these categories is closely related.

The regional geologic and seismologic studies involve investigation and evaluation of the physiography, stratigraphy, tectonics, and geologic and seismic history of the area. These studies identify the seismic events and associated geologic features that together define the most significant earthquakes used to evaluate the site response.

The site geology and soils investigations determine the local geologic conditions, including the soil profile and the rock and soil properties required for static and dynamic design. The soil dynamic properties required include the shear modulus, damping ratio, Poisson's ratio, mass density, and shear strength. Of these, the shear modulus and damping are most significant in seismic response calculations. These soil properties are obtained from a field exploration and laboratory testing program consisting of borings, geophysical surveys and other field measurements, subsurface soil sampling, and laboratory tests.

The engineering phase involves evaluations and engineering studies necessary to determine the ground motion criteria for the site and procedures for evaluation of potential site failure conditions such as liquefaction.

There are several definitions in 10 CFR 100 that warrant elaboration. First, the NRC criteria define two levels of earthquake ground motions for which a nuclear plant must be designed: the Safe Shutdown Earthquake (SSE) and the Operating Basis Earthquake (OBE). Typically, these earthquakes are obtained by correlating past earthquakes with known geologic structures or - in the absence of such features - with tectonic provinces.

The SSE represents the maximum possible earthquake event at the site. This hypothetical event may not have occurred at the site

in historic times, and therefore, it is primarily based on a detailed investigation of the regional and local geology, regional seismology, and characteristics of the underlying soil materials. The nuclear plant should be designed for this earthquake so that all systems necessary to protect the health and safety of the public will remain functional both during and after the event. Structures and components may suffer severe damage from the SSE, but the design must allow a safe and orderly shutdown subsequent to the seismic event. The allowable lower bound for the peak horizontal ground acceleration at the site for an SSE is 0.1 g.

The OBE represents the earthquake event that can be expected to occur at the site during the operating life of the plant. This earthquake, like the SSE, is based on a detailed investigation of the regional and local geology, regional seismology, and characteristics of the underlying soil materials. The nuclear plant should be designed for this earthquake so that those systems of the plant necessary for continued operation without undue risk will remain functional both during and after the event. If the OBE is exceeded at the site, the plant must shut down until it is demonstrated that critical features of the plant have not been damaged. Currently, the allowable lower bound for the peak horizontal ground acceleration at the site for an OBE is 0.05 g or one-half the SSE, whichever is greater.

Second, a fault is a tectonic structure along which differential movement of adjacent earth materials has occurred parallel to the fracture plane. Surface faulting is differential ground movement at or near the surface caused by fault movement. The NRC criteria for a fault to be considered capable of surface movement during plant lifetime requires one or more of the following:

1. Movement at or near the surface at least once in the last 35,000 years and more than once in the last 500,000 years.
2. Fault-related instrumentally determined microseismicity.
3. A relationship to an active fault such that movement on one fault could reasonably be expected to be accompanied by movement on the other.

Third, tectonic province is a region with relatively consistent geologic features. The province boundaries are determined through a regional analysis of the geologic and tectonic environments and the seismic history of the area (Coulter et al, 1973). The tectonic province concept is particularly important where earthquake epicenters cannot be related to known faults or other specific major tectonic structures. An understanding of these definitions, which are unique to the ERDA and the NRC, is crucial to an appreciation of the current methodology for design of dispersed nuclear power plants.

Regional Geology

The geologic characteristics of the site region should be investigated in sufficient detail to provide a clear understanding of the physical processes involved in the geologic history of the area while emphasizing the potential for future seismic activity. The size of the region to be investigated is both area- and site-dependent and may be limited to 200 miles around the site or may include an entire tectonic province depending on the regional tectonics.

The geologic investigations begin with an evaluation of available literature. This is correlated with existing published and unpublished geologic maps. The preliminary stratigraphic relationships, tectonic framework, and geologic history are then determined, resulting in a preliminary geologic map. Aerial photographs and standard geologic field mapping techniques are used with subsurface studies to prepare the final geologic map and establish the physiography, stratigraphy, and structural geologic conditions of the area.

Physiography

Detailed site and aerial reconnaissance is performed to identify important geologic surface features (land forms, drainage patterns, areas of surface water collection, etc.), and to evaluate the relationship between such features and probable subsurface conditions. The relationship between the regional and site physiography should be considered. The final product is a regional physiographic map.

Stratigraphy

The stratigraphic investigations include an analysis and description of the lithology, composition, mode of occurrence and age of the various geologic units underlying and surrounding the site. Regional geologic maps are prepared. Stratigraphic column and geologic cross sections relating regional and local geologic conditions to the site are prepared. This information is developed from the literature, field mapping of outcrops, well logs, and special borings.

Tectonics

Investigations of the tectonics include identification and evaluation of all tectonic structures in the region, whether buried or at the surface. These structures include folds, basins, domes, and faults. The possible effects of man-related activities near the site should be considered, such as the earthquakes produced by the loading effects of dams or reservoirs, the pumping or extraction of subsurface water, or the extraction of minerals.

Identification of all capable faults within 200 miles of the site is of particular importance. They may be observed directly from exposures in the field or detected during well drilling or boring. Usually, their identification is based on more indirect evidence such as gravity or aeromagnetic surveys, acoustical or seismic profiles, black-and-white, color, or infrared aerial photography, multispectral satellite imagery, and side-looking radar imagery. In particularly difficult situations, final assessment is often based on angled borings, trenching, and tunneling.

As defined above, a capable fault is one along which movement has occurred in geologically recent times. Various dating techniques are used to evaluate these potential fault movements:

1. The limiting age of 35,000 years is established indirectly by using geologic methods or absolutely by using radioactive carbon techniques.
2. The limiting age of 500,000 years is established indirectly by using:
 - Geologic methods, which include paleontologic and stratigraphic relations, weathering profiles, and geomorphic features.

- Paleomagnetic methods based on remnant magnetism.
- Radiometric methods measuring radioactive decay.
- Geochemical methods which measure the concentration of specific trace elements or oxides.

Once capable faults are identified, their potential for producing a major earthquake must be evaluated. Thus, the following features of those faults longer than those lengths indicated in Table 1 should be determined:

1. Fault length.
2. Magnitude and nature of past displacement.
3. Geologic history of movement, particularly the age of the latest.
4. Relationship of fault to regional tectonic structures.

TABLE 1. Minimum Fault Length Versus Distance from Site (AEC, 1972)

<u>Minimum Distance from Site, (miles)</u>	<u>Minimum Fault Length to be Considered (miles)</u>
0 - 20	1
20 - 50	5
50 - 100	10
100 - 150	20
150 - 200	40

A tectonic map should be prepared showing the location of major faults, folds, warps, and other structural features, defining them in terms of dimensions, attitude, and age. This map should also show areas of actual or potential surface or subsurface subsidence, uplift, or collapse from tectonic or human activities.

Geologic History

The final step in the regional geology investigations is the reconstruction of the geologic history of the area, emphasizing late Tertiary and younger tectonic history. This history is of prime importance as it provides the regional framework for establishing the pattern and age of major deformations including recent faulting.

Site Geology and Soil Engineering Properties

As depicted in Figure 1, site geology and soil engineering investigations are required at nuclear power plant sites. It is convenient to include them in this section since many of the studies required are natural follow-ons to the work performed in the regional and site geology investigations.

The overall purpose of these investigations is to define all aspects of the site geology, including the soil and rock profiles and the material properties required for foundation design, stability evaluations, and seismic response calculations. These investigations result in the determination of the soil and rock classifications, the thickness and lateral distribution of the soil strata, groundwater levels, and the engineering properties of the bedrock and of each soil layer down to bedrock or to relatively firm materials. Both field and laboratory investigations are carried out.

Field Data

Field investigations are carried out using borings, trenches, and geophysical techniques such as seismic refraction surveys, inhole surveys and electrical resistivity surveys.

Laboratory Data

Laboratory testing is carried out to classify the soil and rock, determine the unit weight, relative density, shear modulus, damping, Poisson's ratio, bulk modulus (rarely), and static and dynamic strength.

A summary of the field and laboratory testing is shown in Table 2.

Seismology

A summary of the seismology and ground motion requirements is presented in Figure 2.

The potential for earthquake activity near a nuclear power plant site is determined from the seismic history and characteristics of the site and the surrounding region, and their relationship to the geologic conditions. This requires a thorough research, review, and evaluation of all historic earthquakes that have affected, or could reasonably be expected to have affected the site. Listings of these earthquakes should be prepared and should include:

1. Date of Occurrence.
2. Epicentral Intensity and Magnitude.
3. Epicenter Location.

This information is used to compile:

1. Epicentral Maps. Two maps are required, each showing tectonic structural features and earthquake epicenters in the site vicinity. One shows the epicenters of all earthquakes within 50 miles of the site and the other epicenters of all earthquakes equal to or larger than intensity IV (MM) within 200 miles of the site.
2. Correlation of Epicenter Locations and Tectonic Structures. The epicenters, or locations of highest intensity, of historic earthquakes should be correlated with tectonic structures having any part within 200 miles of the site.

TABLE 2. Determination of Soil Material Properties Required
for Vibratory Ground Motion Investigations

<u>Property</u>	<u>Type of Test</u>	<u>Soil Materials</u>	<u>Most Commonly Used</u>
Classification	Field	All Types	Visual inspection
		Granular	Visual inspection; grain-size; natural water content
	Laboratory	Cohesive	Visual inspection; Atterberg limits; natural water content
Unit Weight	Field	All types	In-place density
	Laboratory	All types	Undisturbed specimen
Relative Density	Field	Granular	Standard penetration
	Laboratory	Granular	Undisturbed specimen, if obtainable
Shear Modulus*	Field	All types	Geophysical
	Laboratory	All types	Triaxial; simple shear; resonant column
Damping*	Laboratory	All types	Triaxial; resonant column
Poisson's Ratio	Field	All types	Geophysical
	Laboratory	All types	Triaxial, usually estimated
Bulk Modulus	Laboratory	All types	Triaxial; not commonly measured
Static Strength	Laboratory	Cohesive	Unconfined compression
Dynamic Strength	Laboratory	All types*	Triaxial

FIGURE 2. Seismic Input Design Procedures

3. Rates of Attenuation with Distance. If possible, isoseismal maps should be compiled.
4. Recurrence Intervals. If sufficient data are available, the frequency of occurrence of earthquakes of a given size should be determined. These recurrence intervals provide useful supporting data for defining the design earthquake.
5. Identification of Appropriate Empirical Data. Typically, earthquakes are reported in terms of magnitude, intensity, and epicentral distance. Empirical charts relating these parameters to peak acceleration, duration of strong shaking, etc., are available in the literature and must often be used to estimate ground motion at nuclear plant sites.
6. Other Data. When available, other data are reported, such as the duration of strong shaking, the area within which the earthquake was felt, important damage effects (such as landslides, liquefaction, or subsidence), tsunami, etc.

The purpose of the geologic and seismologic studies of the region and site is to establish the SSE and OBE. These studies provide the information necessary to identify the seismic events and geologic features that define the most significant earthquakes to consider in evaluating vibratory ground motion effects at the site.

The most significant earthquakes are determined from an evaluation of the seismology, geology, and seismic and geologic histories of the site and surrounding region. The most severe earthquakes associated with tectonic structures or tectonic provinces in the region surrounding the site are identified by considering the historic earthquakes and other factors such as duration and felt areas, damage effects, recurrence intervals, earthquake magnitude vs. fault length, and displacement on the fault. If capable faults exist in the region, the most severe associated earthquake should be determined by also considering their geologic history. The general procedures for defining the most significant potential earthquakes are as follows:

1. Where the historic earthquakes of greatest intensity can be correlated with a fault or tectonic structure near the site, the epicenters of these events are assumed to be located at the point on the fault or structure closest to the site.
2. Where the epicenter of a large earthquake cannot be related to a fault or tectonic structure it must be identified with a tectonic province. If the site is also within that province, the earthquake is assumed to occur at the site. Otherwise, the earthquake is assumed to occur at the point along the boundary of the tectonic province that is closest to the site.

Once potential significant earthquake events are located, the basic design parameters required for the seismic response studies can be determined. These parameters include the peak ground acceleration, the duration of strong shaking, and peak rock acceleration. They are obtained from both the intensity-duration data for the region and from the empirical data that relate these parameters to the magnitude, intensity, and epicentral distance of the earthquake event.

SOIL STRUCTURE INTERACTION

The previous section described the present methodology for determining the seismic design bases for dispersed nuclear power plants. This section reviews the next step in the overall seismic methodology chain and the effect of the seismic input on the site features, and evaluates the modifications made on the seismic input through interaction with the site structures and other construction works.

The dynamic interaction of structures and their supporting soil media has been the subject of investigations spanning at least the past 40 years. While much of the initial work focused upon machine foundation vibration problems and development of suitable analytic models for prediction of structure response to dynamic loads, it has long been recognized that soil effects can be significant in the seismic response of large-scale structural systems. The general observation has been made that, in the case of the

light flexible structures comprising the bulk of conventional construction, soil influence in modifying the dynamic response of the structures is usually small. The exception to this observation is the case of conventional structures founded upon very flexible soil media (typical shear wave velocities less than 1000 ft/sec). At the other extreme is the case of massive rigid structures, such as nuclear power containment structures and concrete dams. For these structures, interactive effects will generally be significant if not dominant in structural seismic response, with interaction modifying both the base response and structural and equipment response at higher elevations in the structure. The importance of interaction effects depends, in a specific case, upon the relative mass, stiffness, and damping characteristics of the structure and surrounding soil. For massive, stiff structures, the dominant interaction contribution comes from rocking; rocking can produce significantly higher structural response at locations away from the center of mass, with peak accelerations increasing by an order of magnitude over the input free-field accelerations. While nuclear containment structures are typically sited at locations possessing "good" soils from the point of view of stability and other dynamic characteristics and the structures are partially embedded in the soil media, interaction is typically of major importance in determining the structure and equipment loads induced by potential earthquake excitation.

The significance of soil-structure interaction for nuclear power plants and analytical techniques for dealing with the associated phenomena have been the subject of intensive investigation and publications since the late 1960's. However, experimental investigation of interaction effects and validation of analytical procedures has lagged far behind theoretical developments, due in part to the paucity of strong-motion earthquake records taken in any structures, let alone nuclear containment structures.

Rock Site

When the nuclear power plant structures are founded on rock, the soil structure interaction (SSI) requirements are usually very simple. Because interaction effects on rock are negligible, the seismic input is applied directly to the structures.

Soil Site

When the nuclear power plant structures are founded on soil, specific SSI calculations are required. The methods acceptable to the NRC are depicted in Figure 3, which will serve as the basis for the review:

1. Deconvolution Model

This is a one-dimensional model based on the assumption that horizontal earthquake motions are transmitted by vertically propagating shear waves and vertical earthquake motions by vertically propagating compressive waves. Although the model requires viscoelastic soil layers, the method takes account of soil nonlinearities by an equivalent solution for the response in which the nonlinear soil properties (shear modulus and damping factor) are consistent with the strains experienced. The approach has been termed a deconvolution because the calculations are made with Fourier Transforms of the input. The output from the calculations is simply the transform of the input times the transfer function of the site. If the output is a bedrock spectrum, the process is termed a deconvolution. A convolution, on the other hand, yields a surface spectrum, given a bedrock spectrum.

2. Synthetic Regulatory Guide 1.60 Time History

The major output of the section, Seismic Input, is the peak acceleration for the SSE and OBE. This parameter with Regulatory Guide (R.G.) 1.60 spectra determines the spectral shape and value for the site seismic input. However, time history analyses are performed as a time history is required. The procedure by which such a time history is generated is as follows. First, it is assumed that the response spectrum amplitudes are the same as the Fourier spectrum amplitudes. This is a conservative assumption for the zero or lightly damped response spectrum. Then, a Fourier phase spectrum is calculated using a random number generator and the inverse transform of the two spectra is calculated. This, of course, consists of an infinitely long wave train and thus must

FIGURE 3. Site Response Soil-Structure Interaction Design Procedures

be shaped. The shaping is usually in accordance with the analysts' judgment constraining total duration and duration of strong shaking. A check is then made to examine the agreement between the response spectrum of the time history and the design response spectrum. If the agreement is unacceptable, iterative techniques are employed to force agreement.

3. Vary Soil Properties

The soil shear and bulk moduli, mass, and damping are varied about the mean properties according to the scatter obtained in the laboratory test results. The intent here is to incorporate anticipated uncertainties into the design chain. The soil shear modulus is usually derived from in situ or laboratory measurements on the shear wave velocity and these measurements are rarely repeatable within $\pm 25\%$. This means that the derived values of the shear modulus usually scatter $\pm 50\%$. The NRC, therefore, requires that applicants vary the shear modulus $\pm 50\%$ or as the scatter in the data indicates, to account for this variability. Deconvoluted results are obtained for the mean, maximum, and minimum properties.

4. Envelope 60% Spectra

The results of the three deconvolutions in the preceding step are three time histories are used as the input to three response analyses using the deconvolution model and the respective soil properties, and three spectra at the structure foundation level obtained. These analyses and the three base time histories are used to obtain a single time history which when input to the deconvolution model with mean soil properties in a response analysis will result in a response spectra at the foundation level of the structure that is equal to or greater than 60% of the starting R.G. 1.60 spectra. This is the time history used for the SSI response analyses.

This process is admittedly conservative and an alternative acceptable to the NRC is to use the three base time histories and perform

three SSI response analyses. This is less conservative but more expensive. This modification is generally desirable in high seismic areas.

5. Develop Simple Structural Model

This structural model is used in the SSI model of the site. Typical models are represented by several tens of nodes and are thus not as detailed as the ones used in the detailed structural analyses which consist of hundreds of nodes.

6. Select Soil-Structure Interaction (SSI) Approach

Two approaches are presently acceptable. One models the soil indirectly by using equivalent springs and dashpots and the other models the soil directly by using the finite element model. Until recent ACRS meetings, the latter method was preferred but the situation is unclear at this time. The probable result will be that the soil spring method will become more acceptable.

7. Soil Spring Approach

The soil parameters to be selected include equivalent soil "springs" and "dashpots" (possibly frequency dependent). As noted above this method may see a resurgence in popularity. This is because the former differences between the soil spring and finite element approaches are being reconciled, the NRC appears more receptive, and the soil spring method is simpler and less expensive than the finite element method. Details of methods acceptable to the NRC will have to await continuing licensing activity.

8. Finite Element Approach

Heretofore the finite element approach has been preferred in most applications. The model is two- or quasi-three-dimensional. A number of decisions must be made including the lateral (and possibly vertical) extent of the model, the mesh refinement (this determines the highest frequency transmitted faithfully), the soil layering (horizontal layers are assumed), and methods for approximating

radiation damping (transmitting boundaries, lateral refinement) being some of the most important. Sometimes two soil layerings are selected corresponding to the plant "North-South" and "East-West" soil profiles, and two sets of SSI analyses performed. Occasionally SSI analyses are not performed for the vertical earthquake component (less interaction occurs) or for the OBE (the SSE results are scaled).

9. SSI Calculations

The major objective of the soil-structure interaction calculations is to obtain basemat response for subsequent detailed structural analyses. A second objective can be to obtain floor response spectra but these are also obtained in the detailed structural analyses. For certain sites the SSI calculations will also be used for foundation stability evaluations such as liquefaction analyses. In this latter case for problem sites the SSI calculations are sometimes performed also using scaled real earthquake records rather than R.G. 1.60 time histories.

STRUCTURAL ANALYSIS

The previous two sections both focus on the third major element in the seismic design chain, Structural Analysis. Seismic input and soil structure interaction result in the basic definition of the loads to be used in structural analysis.

As an introductory comment, it is noted that the greatest changes in seismic design will be due to: 1) the improved seismic strong motion data base that will accrue with time, 2) improved earthquake source and transmission characterization, and 3) improved knowledge of soil and soil-structure behavior during strong excitation, rather than to changes incorporated in the structural area. This is because a great deal of analytical and experimental effort has already been performed in the structural design area. This is not to say that new knowledge will not develop in the structures area. The point is that changes in the structural design area will result more from decisions, for example, to take credit for reserve structural strength using inelastic methods that are currently available, than

being forced by the development of new knowledge. Relative to seismic input and soil-structure interaction, a great deal of readily available structural technology already exists.

The basic NRC guide is the Standard Review Plan, Sections 3.7 and 3.8. The present structural response methodology is described in Figure 4. No attempt will be made to describe this chain in detail, or to develop a similar chain for design, because the discussion would become mired in details. Rather, a few significant aspects will be discussed.

1. Mathematical Modeling

A great deal of variability exists in the detail of the mathematical models used. For example, even at the same design level a complex three-dimensional structure can be found to be represented by models ranging from a simple two-dimensional "stick" one, to a complete three-dimensional finite element representation of the entire building, to complete three-dimensional models of all the structures of an entire floating nuclear plant. In a number of cases involving even more detailed levels of analysis and design, more refined models of local regions of the larger models are made, and there is also a great deal of variability in how this is accomplished. It is not an easy task to rationally decide the requirements of models and clear guidelines do not yet exist.

2. Analysis Methods

In the SSI step only the time history (time or frequency domain) type of analysis method was used. This lack of variability does not exist in the structural analysis and design area. The methods used include:

Nonlinear (implicit, explicit, degrading, cracking, gaps, contact, impact, etc.)

Time History (modal, direct integration, implicit, explicit, frequency domain)

Response Spectra

FIGURE 4. Structural Analysis (Design Procedures)

Quasi-Static (statically applied loads obtained from a dynamic response analysis)

Static (non-transient loads)

Thermal, thermal/structural

3. Combination of Three Earthquake Components

The requirement to design for three earthquake components introduces a significant complexity into the design-analysis process. Much of this is in the nature of "bookkeeping," that is, keeping track of results and combining them according to an established method.

There are two basic methods which can be used: 1) combine results from three separate seismic analyses, and 2) obtain results from one seismic analysis using three stochastically independent seismic inputs applied simultaneously. An allied complex problem is the combination of seismic and other loads in the required load combination design formulas.

4. Equipment and Safety System Design

Just as in the case of the effects of seismic input and soil structure interaction on structures, one of the most significant effects of the structural analysis and design methods used is on equipment loads and the design of safety systems.

SEISMIC OPERATING CRITERIA

The final topic to be considered in the review of the present seismic methodology is seismic operating criteria. The major question in this area is whether it is advisable to require a seismic trip, automatically, upon detection of a seismic event.

Existing Seismic Instrumentation and Regulations

There are presently no requirements for a seismic trip on commercial power reactors but certain seismic instrumentation must be provided for sensing and recording purposes.

Seismic instrumentation at nuclear power plants consists mainly of triaxial time-history accelerographs, peak accelerographs, seismic switches, and response spectrum recorders. The purpose of this instrumentation is to record an earthquake and monitor the plant's response. Information from the instrumentation can then be used to help establish whether the OBE has been exceeded and if it has to shut the plant down.

Seismic Standards

The regulations and standards that determine the present seismic instrumentation requirements are Regulatory Guide 1.12 and ANSI standard N18.5 (ANSI, 1974). A proposed standard, ANS 2.10/N643, is under review and specifies the response the plant operator should make based on the instrument readings following a seismic event. Basically, this standard relies on a controlled, manual shutdown in a two-step approach.

Whether the OBE has been exceeded is determined in the first step. This is indicated if a minimum number of points of the recorded response spectrum have exceeded the OBE design response spectrum or if there is an equipment malfunction. In either case, the plant is shut down in a controlled manner which may take 5 to 10 hr. Restarting the plant may require the approval of both the NRC and the plant owner. There is no clear criterion to assess the advisability of restarting the plant, so once a plant is shut down it may be down for some time. There is really only one data point of this type, the June 7, 1975, event at the Humboldt plant, and in this case the plant was not operating. In this case the owner inspected the plant, reported the results to the NRC, and the event does not appear to have delayed startup significantly, if at all.

If, in Step 1, it is determined that the OBE was not exceeded, then the operator continues operation and proceeds to Step 2. In Step 2 the recorded data are analyzed to determine if the design floor response spectrum has been exceeded. If the floor-response spectrum for the OBE has been exceeded, the plant is shut down. The analysis may take up to 1 week.

Note that the intent of the ANSI standard is to enable the operator to determine whether the plant should be shut down and to shut down if the

OBE has been exceeded. In judging this, the operator is to take into account only the condition of the plant and not the need for the electric generating capacity of the plant.

In some cases, detailed structural analyses of the plant may be required.

Current Changes in Operating Criteria

The current requirements, regulations and guidelines are due to be enlarged very soon. Perhaps the most significant revision in licensing requirements for operating plants will be embodied in the program for reevaluation of operating plants now being formulated by NRC. This program introduces the concept that all existing plants must be formally reviewed to ensure that they exhibit a "level of safety" consistent with the current state-of-the-art, and provides a mechanism for reviewing future regulations to ensure that any significant developments are back-fitted.

Thus, the formal review procedure will be open ended over the life of the plant. This philosophy has developed as a result of congressional pressure, criticisms by the ACRS, and a growing awareness by the NRC staff that for older plants the basis for regulatory compliance is not well documented.

In principle, this program is consistent with 10 CFR 50.109, which allows the NRC to impose backfits that provide "substantial additional protection" to public health and safety, but its implementation could escalate the application of backfits. NRC has informally announced that the general approach would be to compile a list of all potential safety issues (possibly as many as 300), identify the specific items that apply to each plant, and make a finding for each issue as to why corrective action should or should not be implemented.

3.0 POTENTIAL FUTURE SEISMIC CRITERIA

In Section 2, the present seismic criteria used for dispersed nuclear facilities were reviewed. It was noted that the criteria are somewhat dynamic in nature and therefore some attempt at time extrapolation is warranted. Furthermore, nuclear energy centers, if subjected to the existing criteria used for dispersed plants, may be subjected to a greater magnitude of risk because of the centralization of facilities and the associated vulnerability to large-scale seismicity. Therefore, this section is designed to delineate anticipated near-term changes in the present criteria and to recommend areas where additional renovations may be considered by the regulatory agency in the long term. These recommendations will be made in reference to the unique aspects of Nuclear Energy Centers as previously discussed and accordingly, should be reviewed in such a context.

POTENTIAL NEAR-TERM CHANGES

To set the stage, it is useful to summarize changes in the licensing process which may be anticipated in the very near future. This summary is based on:

- Informal discussions with NRC licensing personnel
- Review of recent ACRS meetings
- Discussions with other consultants engaged in the seismic design of nuclear power plants.

Possible changes in the licensing process may not be implemented as regulatory guides for some time, but could be introduced into the review policy over the next 6 to 12 months. Based on present trends, the policy changes will be gradual and will necessarily be accompanied by confirmatory research. It is important to stress at this point that confirmatory research is required for each of these items; the research required for validation, however, is relatively modest compared to that which may be required for many of the items discussed later in this section.

Seismic Input

With regard to the near-term changes in the seismic input, it is likely that the minimum SSE peak acceleration will be increased to 0.2 g and that of the OBE to 0.1 g. This is based on a more careful analysis of seismic records which indicate that the East Coast, where the minimum levels are usually applied, has lower attenuation characteristics than previously thought.

Another gradually emerging policy change concerns R.G. 1.60. As described previously, the ground motion at a site is currently represented by a response spectrum that is site-independent. The NRC is already relaxing the site independency of ground motion on a case-by-case basis. Formal guidelines will probably emerge outlining acceptable site-dependent and earthquake magnitude spectra.

Soil-Structure Interaction

With regard to near-term changes in soil-structure interaction, much greater emphasis will be placed on site effects. Guidelines will probably emerge, establishing such site modeling criteria as:

- How to model the soil properties (equivalent linear or nonlinear).
- How to incorporate soil hysteretic damping.
- The circumstances under which a deconvolution calculation is inappropriate (such as a shallow soil layer over bedrock).

Another important shift in policy that may emerge is the requirement to determine the site and structure response to several synthetic accelerograms. Each of these seismograms would envelop a specified response spectrum (which might be magnitude-dependent), but would differ in their duration and phase.

Further, a great deal of effort will be devoted to improving and specifying techniques to obtain soil properties in situ. There is a great deal of concern regarding the validity of laboratory soil properties and

the corresponding models of large earthquake strains. The hope is that sufficiently large strains can be generated by a down-hole or cross-hole device to circumvent this uncertainty.

In the soil-structure interaction design component attention will be formally directed at modeling other modes of seismic energy (besides vertically propagating shear waves). Most effort will center on the traveling wave effect on a large foundation. Several analytical techniques have been proposed and some have actually been employed to address specific licensing problems. Informal policies regarding the use of these models will probably first evolve from the ASLB and the ACRS hearing process and formal policies will follow verification.

Also in the soil-structure interaction design component, the structural plane strain two-dimensional modeling will come under increased scrutiny with the result that simpler three-dimensional models will become acceptable provided they accurately model all the degrees of freedom of the structure. The use of lumped mass methods in particular, despite other modeling uncertainties, will be permitted in a wider variety of applications.

Policy will also be changing with regard to the two-dimensional modeling of the soil, but for a different reason. The present two-dimensional modeling requires that the analyst develop a two-dimensional model of a three-dimensional site and this is usually accomplished by selecting a cross section through the site and assuming that every other cross section parallel to that selected is identical. Even though the site response might be derived from the examination of the response of several different cross sections, this does not explicitly take account of the effects of "out of plane" structures. For complex sites, this could be very significant. Guidelines will emerge which will set forth the limitations of the two-dimensional modeling and indicate how two-dimensional cross sections should be selected in those circumstances where a two-dimensional response is acceptable.

Structural Analysis

In terms of the structural analysis component, one can expect a near-term change to reflect the increasing concern with the torsional response of the structure. As with all these near-term changes in regulatory policy, awareness of the significance of the torsional response has evolved from issues raised on specific licenses. The changes with regard to the structural response will consist of guidelines indicating the circumstances under which the torsional response is important, both geologically and structurally, and indicating acceptable modeling techniques.

Operating Criteria

Finally, with regard to operating criteria, it is worthy of note that within the last year the NRC formally organized, and heavily staffed, a Division of Operating Reactors (DOR). This new organization is certain to issue many new guidelines and regulations, but it is presently difficult to anticipate them with any detail. There is, however, one item that DOR will almost certainly take a stand on, the advisability of seismic scram systems. This is a very controversial point because spurious scrams and scrams during small nonhazardous earthquakes could cause significant disruption of electric systems through the sudden loss of electric power and potential damage to plants as a result of thermal shock. Nevertheless, the scram system may provide an additional margin of safety and thus warrants careful consideration.

LONG-TERM CHANGES

Based on the best information available, the above paragraphs have summarized potential short-term changes in seismic design criteria. These changes are relatively easy to identify since they all represent a natural evolution of the current procedures. It is anticipated that most of these changes will be incorporated in one form or another in the next few years.

No attempt will be made to predict long-term criteria development for NECs. However, three subject areas will be presented from which

criteria may be derived in the future. The unique nature of Nuclear Energy Centers may motivate the development of criteria in the following areas:

- The breadth and depth of seismic input analysis
- The use of site-specific earthquakes and front end oriented analytical and numerical models.
- The use of continuous, real-time seismic prediction techniques.

The following section is devoted to a relatively detailed discussion of the available tools and techniques that may function to meet potential criteria in the aforementioned areas.

4.0 FUTURE SEISMIC CRITERIA--TOOLS TO MEET THE CHALLENGE

One of the central points of this study is that NECs will be sensitive to anything that can affect any significant percentage of the facilities in a single event. Seismic events are clearly in this category and therefore seismic criteria for NECs may be somewhat different from those now in existence for single plants. The evolution of this criteria will necessarily parallel increased understanding of seismic processes and effects, the development of tools to generate necessary data, and the implementation of effective methods for evaluating the generated data. Therefore, some of these new or relatively unexploited tools and methods will be discussed in this section. Given the centralization of capital and generating capacity, NEC sponsors will undoubtedly take great interest in protecting against the potential disabling effects of a large earthquake. This will probably occur on a voluntary basis; however, to ensure compliance and uniformity new criteria will be drafted and enforced by the regulatory agencies.

SEISMIC INPUT AND RESPONSE ANALYSIS^(a)

Geologic requirements for siting energy centers will obviously require an extensive regional seismic analysis of greater breadth and depth than is currently exercised. The technology presently available to conduct the desired full spectrum of studies is not totally available and as such, advancement of present technology and development of new technology are required. The following list illustrates tools and techniques that are generally available but are not utilized to their full potential or could be greatly enhanced by additional research and development. The list is designed to complement the classical techniques that were delineated in Section 2.

^(a) A portion of this section has been derived from the efforts of the United States Geological Survey and specifically, the Earthquake Hazard Reduction Program Staff (G.S.C. 701).

Remote Sensing

Remote sensing systems operating from aircraft and spacecraft platforms can collect much of the data needed for regional (hundreds of miles) tectonic studies. This is a unique source of data for identification and analyses of regional fault patterns and geologic structures. More sophisticated and flexible techniques are needed to rapidly analyze these data and produce the desired enhanced and filtered output formats. Advanced airborne remote sensing systems should be developed to collect specific data types on a local scale to complement the regional satellite data.

Electromagnetic Exploration

A variety of electromagnetic methods utilizing a wide range of wavelengths are available for shallow to deep crustal investigations. The depth of penetration and resolution of the mapping depends on the selection of wavelengths, but the effective range extends from fractions of meters to tens of kilometers. Natural signals due to lightning (VLF-LF) and disturbances in the geomagnetic field (ULF) as well as a broad range of man-made signals (pulse and continuous) from high power transmitters are feasible electromagnetic sources. Various methods are available for data reduction and enhancement; however, research in data interpretation is necessary especially in developing analytical, numerical, and experimental techniques applicable to the detection of major crustal dislocations.

Geomagnetic and Gravity Surveys

Special techniques using high density aeromagnetic and gravity data for fault detection are available, but there is much room for improvement in data reduction techniques. Methods utilizing directly measured gradients of the magnetic field can potentially yield additional geologic detail. Techniques based on the Poisson relationship between magnetic and gravity anomalies and utilizing simultaneously collected magnetic and gravity data could remove some of the ambiguity inherent in present methods of analyzing both magnetic and gravity data.

Acoustical Methods

Standard land-based reflective and refractive seismic surveys are in common practice. However, new techniques such as cross-borehole tomography, holography, and surface (Rayleigh) wave analysis are proving feasible for subsurface evaluation. Furthermore, because of their linear character and long extent, faults often intersect marine and inland water bodies. Thus, water-based sub-bottom reflection profiling techniques appear to have merit.

Deep Stratigraphic Correlation

Subsurface stratigraphic information and sequence correlation are required from near surface to great depths for construction and verification of a geological model.

The information could be obtained through limited deep drilling and logging of test boreholes. Both in-situ geophysical logging and drill core analysis can be used for acquisition of the data. Some work is needed to improve resolution for in hole determination of density, porosity, permeability, magnetization, magnetic and electrical susceptibility, fractures, radioactivity, sonic velocity and pore fluid and petrological identification.

Tectonic Measurements

Telemetered tiltmeters could be used to monitor strain changes continuously at many locations in order to document slow and rapid crustal deformations. In addition, surveying techniques such as the laser interferometer for leveling and trilateration could be implemented to monitor local or gross regional deformations. Finally, creepmeters and short alignment arrays should be placed within fault zones to measure small displacements.

Heat Flow Measurements

Geothermal logging equipment and interpretive techniques could be implemented to develop information on temperature as a function of depth in the crust and upper mantle. Any detected anomalies could indicate weaknesses in the local crust that may be associated with faulting.

Regional Tectonic and Structural Modeling

Seismic risk evaluations are usually based on meager geological and historical earthquake data. More details and depth of knowledge about local and regional tectonic processes are needed, particularly for siting major nuclear power centers.

Methods should be implemented to manipulate, superimpose, and graphically display large quantities of diverse geological, geophysical, and hydrological data. In addition, this should include multiparameter correlation of recorded microquakes, strain patterns, strain events, and other features to search for evidence of propagation of strain or slip events. Numerical and physical models could be developed to study and describe large-scale crustal plate movements as well as regional and local faulting and folding.

Adequate Staff and Hardware Facilities

Prior to, during, and subsequent to construction, adequate staff and computer facilities should be available for maintaining and updating a dynamic computer-based model of the crust and upper-mantle earthquake-generating system, for evaluating the significance of monitored field data in terms of the state of the model and for formulating subsequent uses of the model.

Passive Seismic Techniques and Site-Specific Earthquake Simulations

These two methods appear to show considerable potential for advancing the capabilities of earthquake hazard reduction and seismic input characterization. Therefore, they will be discussed in much more detail in subsequent parts of this report.

Seismic Engineering

- Develop a basis for estimating the principal characteristics of strong ground motion such as spectral characteristics, attenuation rates, influence of the source, the travel path, and local site conditions.

- Install two-dimensional arrays of strong motions instruments in the structures and in the free field to monitor spectral characteristics and attenuation of earthquakes and the influence of local geology, soils conditions, and topography.

Advanced Techniques

Some instruments and methods require further testing or development or are too costly for extensive use at present. Nuclear Energy Centers may provide the incentive for accelerated research in many of these areas;

- In-situ stress measurements by hydraulic fracturing or borehole strain-relaxation measurements
- Quartz-tube strain meters or other short base shallow-burial strain meters
- Multibeam laser-ranging instruments to increase the precision of free-air-path distance measurements
- Long-period, broad-band, large-dynamic-range seismographs to record a broader spectrum of ground motion for improved studies of earthquake sources
- Water-level recorders and volumetric-strain meters of high stability and sensitivity
- Stable high-sensitivity recording magnetometers to search for magnetic precursors to seismic events
- Widespread systematic monitoring of water composition at flowing springs or wells to search for geochemical precursors to earthquakes
- Extensive drilling and direct examination and instrumentation of fault zones at depth.

MICROSEISMIC NETWORKS

The use of microseismic networks both during the site selection process and after plant startup could be very desirable.

First, as an aid in the site selection process, such a network would provide valuable information that would supplement the historical seismic record at the site. Generally, seismic zones are defined by a historical record of damaging shocks supplemented in recent years by instrumentally recorded and located earthquakes. One of the most significant problems is the short period of recorded history with which seismologists have to deal. In areas where the mean time between damaging earthquakes may be a thousand years, an historic record of several hundred years can be totally inadequate. For a number of years seismologists have considered the problem of using the much higher rate of micro-earthquakes, which are very small earthquakes with magnitudes less than about 2.0 on the Richter scale, as a statistical measure of activity from which to extrapolate to large but less frequent damaging earthquakes.

As a result of extensive instrumentation in the western United States by the U.S. Geological Survey, it is now clear that micro-earthquakes have a much greater significance for determining fault "capability" and potential earthquake hazards than was previously thought to be the case. Some questions remain, of course, but it is clear that micro-earthquakes are not as diffusely distributed as was previously thought. Whenever they have been studied in detail, they are found to be closely related to geologic structures capable of generating significant earthquakes. This is not to say that every micro-earthquake indicates an active fault, but rather, when a distribution of small events defines a planar region in the earth, this is virtually uncontrovertible evidence of the existence of an active fault.

If an adequate statistical sample is available, there appears to be in many cases a reasonable relationship between the rate of small earthquake activity and that of larger shocks, thus making possible a useful estimate of recurrence times for damaging shocks. The length of time necessary to collect significant data varies widely from one region to another. In general, areas of low seismicity should be sampled over a larger period of time in order to provide dependable statistics. The time intervals thus range from several months to several years.

In addition to the definition of seismic zones, micro-earthquake data can provide important information on the stresses operative by using the first-motion pattern for a number of micro-earthquakes to form a composite focal mechanism characteristic of the region. This can be used to determine whether the type of faulting is likely to be thrust, strike-slip or normal faulting (which has an important bearing on engineering estimates of strong ground motion).

Micro-earthquake data seem most useful when other geological data are ambiguous or difficult to obtain. For example, consider the case of an apparently inactive fault which lacks suitable exposures or materials to provide a date of most recent movement. Under current ground rules, if the date of most recent movement cannot be clearly established as previous to several hundred thousand years, the fault must be assumed to be capable of generating an earthquake. Extensive field efforts at great cost can be put into such an investigation, whereas micro-earthquake information obtained at a relatively small expense may have the capability of providing an unambiguous answer in the event the fault is active. Because this tool is most effective in providing information about active structures rather than inactive ones, it is important that it be used as early as possible in the site selection process. Ideally, a seismic network should be established when the general region has been established and several sites are under consideration. Under these conditions the micro-earthquake technique has the capability to save considerable expense in detailed field investigations at several sites by early identification of potentially active faults.

The operation of a network installed during the site selection procedure could be continued at a very small cost after construction and startup of a plant. The network would serve two important purposes. First, such a network could conveniently be coordinated with a seismic scram system to eliminate spurious scrams and scrams due to non-damaging earthquakes. Second, if run at several gains, the network would also provide valuable information in the event a large earthquake occurred. This information

would assist in verifying site response models, soil-structure interaction models and structure-structure interaction models. Such data have never been recorded. The absence of data and therefore lack of verification of design procedures has been a major factor for concern in the safety of nuclear power plants.

SITE-SPECIFIC EARTHQUAKES

As described earlier, the current methodology for selecting the design ground motion at a site is based largely on Regulatory Guide 1.60 which, in essence, specifies the frequency content of the ground motion. R.G. 1.60 is site-independent in that the same frequency content is considered appropriate for every site. Although the amplitude of the ground motion, which is determined by an estimate of peak acceleration, is very site dependent, analysts are becoming increasingly aware of the physical inconsistencies of requiring identical spectral shapes. It now seems implausible that the ground motion from a nearby small earthquake would have the same frequency content as a large, distant earthquake. Observations such as these have prompted both technical and political speculation that the conservatism in seismic design might be less than once thought. This uncertainty has caused the NRC to regulate the seismic input almost completely on a case by case basis, a system that lacks the uniformity of review for which they strive.

The development of a new site-specific approach to characterize the design ground motion for a facility was therefore greeted with relative enthusiasm by the utilities, the intervenors, and the NRC. This new approach examines the problems from a calculational physics point of view; if the earthquake rupture process can be quantified, then the site-specific ground motions results from the propagation of the stress waves through the earth to the site of interest.

General Methodology

The general methodology is to first obtain a quantitative feeling for the rupture process in the tectonic province containing the site. This is

accomplished by selecting one or more nearby earthquakes whose ground motion has been recorded, and to develop detailed rupture processes for the earthquakes by trial-and-error until the recorded and calculated ground motions are within 10 to 20%. This exercise lends credibility to the calculations and expands one's knowledge of the earthquake processes by providing such detailed physical parameters associated with earthquakes as:

- Rupture orientation and extent
- Rupture velocity
- Fracture sequences
- Dynamic stress drop over the fault surface
- Fault offset.

Having calculated these parameters, one might expect roughly the same parameters on other faults of the same dimensions and mechanisms and in the same tectonic province. Thus, it would seem reasonable to use these parameters in a predictive calculation. If the verification earthquakes are not exactly like the postulated earthquakes then the processes would become elements in a parametric survey and the predicted ground motion would envelop the parametric results. In any case, the credibility and accuracy of such an approach appears to be many times greater than the credibility of any site-independent ground motion spectra.

Finite Element Calculations

The calculational approach to this problem is unique in that it links a very powerful nonlinear finite element code (which calculates the response in the rupture zone) with a newly developed semi-analytical procedure for synthesizing seismic waves in a horizontally stratified visco-elastic earth. This two-stage approach optimizes the use of computer resources and still can provide a high frequency response (20 Hz) out many tens of miles.

The finite element computer code, SWIS, is very versatile and considers either static or dynamic problems in one-, two-, and three-dimensional geometries with equal efficiency. In addition, both nonlinear and linear behavior may be analyzed. The dynamic calculations may be performed using either the explicit or implicit time interaction schemes. Also, for explicit dynamic calculations, SWIS has the capability of varying the time step within the computational mesh. This capability has been quite useful for structure-medium calculations (Sweet, 1976). SWIS has been verified against known theoretical solutions for both continuum and structural analysis problems (Frazier and Petersen, 1974; Sweet et al., 1976; Sweet, 1976).

The SWIS code employs a time-centered explicit method for integrating the equilibrium equations in time. The calculation scheme proceeds as follows:

1. The various global arrays are initialized. These include nodal positions, nodal displacements, nodal velocities, applied nodal forces, and nodal masses.
2. Element calculations are performed to obtain the nodal restoring forces. The steps in this calculation are to:
 - (a) Compute strain
 - (b) Compute stress^(a)
 - (c) Compute restoring forces
 - (d) Repeat operations (a), (b) and (c) for each element in the grid to produce the complete listing of the nodal restoring force.

(a) The nonlinear material models presently available in SWIS are as follows: (Sweet et al., 1976):

- Von Mises/Drucker-Prager model
- Soil and rock cap models
- Variable moduli model
- Tensile failure model
- $P-\alpha$ crush-up model.

3. Integrate the equation of motion to advance the solution by one time step Δt :
 - (a) Compute nodal accelerations
 - (b) Compute advanced nodal velocities
 - (c) Compute advanced nodal displacements.
4. Set $t = t + \Delta t$ and return to Step (2).

This procedure is illustrated in Figure 5.

The sequence of steps outlined above can result in as few as 180 floating-point multiply-and-add operations per three-dimensional element for the special case of rectilinear zoning. This is fewer calculations than are required for multiplying the nodal displacements by the stiffness matrix. Actual calculations generally require about 700 floating point multiply-and-add operations per three-dimensional element and about one third this value for two-dimensional calculations. The use of SWIS for numerically simulating earthquake rupture is described and illustrated in Appendix B. The data for such a calculation includes:

- Numerical Grid
- Geologic Layering (density, wave velocities, and attenuation coefficients for each geologic material)
- Initial State of Stress
- Point of First Rupture
- Coefficients for Sliding Friction
- Rupture Extent

The rather massive three-dimensional simulation provides particle motions and material stresses in the regions close to the rupture surface. The major function of SWIS in the SISPEQ analysis, however, is to produce detailed information on fault slip as a function of position and time. The suitability of the finite element for matching abrupt changes in slip which occur near the crack tip is illustrated in Appendix B. It is these abrupt changes in slip that gives rise to high frequency components in the ground shaking.

FIGURE 5. Schematic of the Computational Sequence for Solving the Equations of Equilibrium Using Conventional Finite Element and SWIS Methods

Synthetic Seismograms

Fault slip, which is computed by SWIS, provides input to PROSE, a newly developed procedure for propagating waves in horizontally layered, visco-elastic earth. Thus, PROSE serves to propagate seismic energy from the earthquake source to points on the earth's surface where synthetic seismograms are produced. Mathematically, this is accomplished by spatially and temporally convolving the fault slip from SWIS with the medium response from PROSE, which is characterized in the form of surface motions due to instantaneous slip at a single point on the rupture surface. The convolutions serve to sum the time-dependent production of seismic energy over the entire rupture surface thereby providing the desired ground motions.

The PROSE algorithm is the only method currently available for analytically synthesizing all of the multiply reflected and refracted P and S waves as well as Rayleigh and Love surface waves in a horizontally stratified medium. The method is based on well-known procedures in seismology (Haskell, 1953, 1963, 1964). As illustrated in Figure 6, the equations of motion, expressed in cylindrical coordinates, are transformed: time (t) is converted to frequency (ω) using a Fourier transform; azimuth (θ) is converted to harmonic wave order (n) using a Fourier series; and radial distance (r) is converted to horizontal wave number (k) using a Bessel transform. No transform is performed on the vertical coordinate (z). The result of these transforms is to produce ordinary differential equations in (z) which are solved analytically for each layer. Continuity conditions are enforced at the layer interfaces and transformed surface tractions are set to zero on the free surface to produce solutions for transformed particle displacements as a function of the independent variables (ω, n, k, z) and the forcing term which results from slip on an infinitesimally small segment of the fault. Except for computer roundoff, solutions are exact and complete. Excessive roundoff errors have been avoided at this point using a procedure similar to that advanced by Gilbert and Backus (1966).

FIGURE 6. Flow Chart for Site Specific Earthquake Analysis

The complete seismic synthesis is obtained by performing inverse transformations on ω , n and k to get the solutions in terms of t , θ , and r , respectively. It is here that PROSE is unique in that the inverse transformations are performed to frequencies in excess of 20 Hz without neglecting any wave types. The details of how this has been accomplished are beyond the scope of this report.

The accuracy of the PROSE wave synthesis has been tested in several ways including comparisons of particular wave types with other seismic methods, e.g., first arrival body waves and later arriving surface waves. Figure 7 shows a comparison of the analytical method with finite element results for a surface load on a homogeneous earth. Figure 8 illustrates the uniqueness of PROSE for producing complete seismograms in a horizontally layered earth. Beside the prominent P-, S-, and surface wave arrivals, there are many reflected and refracted arrivals from seismic energy trapped within the layers. The complexity of the seismogram dramatically illustrates how layering in the earth influences the propagation of seismic waves.

Additional technical details of this promising approach are presented in the appendix.

EARTHQUAKE PREDICTION AND CONTROL

The ability to accurately predict and/or control large earthquakes would obviously have considerable impact on the implementation of the NEC concept at least from the seismic hazard perspective. Therefore, a brief discussion of this research area merits inclusion in this report. For specific technical details the reader should refer to the indicated references. The main point to keep in mind is that it is within reason to anticipate a regulatory guide requiring adequate earthquake prediction capability at a NEC site.

Prediction Methods

Currently two independent methods are being explored: 1) statistical techniques, and 2) geophysical methods. The first uses the catalogued

FIGURE 7. Time Histories of Surface Displacement Resulting from Point Force on a Homogeneous Half-Space Finite Element Simulation Utilized 0.7 km Grid Spacing

POINT FORCE ON LAYERED MEDIA
OVER A HALF-SPACE

FORCE = $\delta(t)$
LAYER PARAMETER VALUES

LAYER NO.	THICKNESS (km)	DENSITY (gm/cm ³)	P-WAVE VELOCITY (km/sec)	S-WAVE VELOCITY (km/sec)
1	0.3	2.0	5.2	3.0
2	0.3	2.1	5.8	3.3
3	0.3	2.2	6.5	3.8
4	0.3	2.4	7.4	4.3
HALF-SPACE		2.7	10.4	6.0

FIGURE 8. Prose Solution for the Surface Displacement at Radius

history of earthquakes in a region as a key to estimating when and where such future events may occur. The second involves the observation and interpretation of certain changes in the physical environment in earthquake-prone regions as indicators of an impending event.

The desired prediction must include the expected magnitude range, the geographical location, the time interval, and the degree of uncertainty. The statistical approach tends to yield information concerning the gross geographical aspects, longer time intervals, and general magnitude ranges. Data base correlations of frequent events, seismically quiescent gaps along plate margins, and epicenter migrations or pattern trends are chiefly used. To improve the resolution and prediction lag time, geophysical precursors show the best potential.

Geophysical methods involve searching for, identifying, and monitoring changes in the physical state of the earth that are precursory to earthquakes. In general the list includes: perturbation in the compressional wave-shear wave velocity ratio, ground dilation, anomalous changes in ground tilt, variations in radon concentrations in ground water, anomalous magnetic fields, anomalous electrical resistivity, the relative abundance of large and small earthquakes, perturbation in water wells, lakes and streams, anomalous animal behavior, and gaseous emissions especially hydroxides have been investigated as potential precursors for prediction. It would appear that any successful prediction method utilizing geophysical parameters will have to incorporate and couple many of the aforementioned observations.

To lend perspective to this potentially fruitful area of research, several of the conclusions from the Panel on Earthquake Prediction of the National Research Council are stated.

1. A scientific prediction will probably be made within the next 5 years for an earthquake of magnitude 5 or greater in California. With appropriate commitment, the routine announcement of reliable predictions may be possible within 10 years in well instrumented areas although large earthquakes may present a particularly difficult problem.

2. In a realistic attack on the earthquake-hazard problem, the development of an earthquake - prediction program and the upgrading of earthquake - engineering design and construction are complementary and equally necessary, and should be carried on at the same time.
3. Predictions of earthquakes should specify time, magnitude, place, and uncertainty, but any reasonable bracketing of these parameters would be useful.
4. At present, the ability to detect and locate an impending earthquake requires a dense distribution of instruments in the quake area. Improved observational networks in areas of high earthquake probability are mandatory if we are to gain the fundamental knowledge on which to build an effective earthquake-predictive program.
5. The physical nature of precursory phenomena is complex, and current models to explain them are crude; improvement of these models will require considerable effort in the field and laboratory, as well as in theoretical studies.

It is important to note that the apparent consensus is: given adequate effort, predictions may be feasible in a time span on the order of 10 to 20 years. This may well be coupled to the critical time frame for NEC siting and construction programs.

Earthquake control, although extremely promising in terms of its impact or consequences, is not currently within the bounds of our technology. Proposed methods such as manipulating pore fluid pressure in a fault zone deserve research support, but should not be seriously considered in siting criteria studies at this point in time.

5.0 SUMMARY AND CONCLUSIONS

The primary objective of this report can be subdivided as follows: 1) to review, analyze and summarize in compact form the existing procedures as encompassed in seismic criteria for the siting and design of individual nuclear facilities, 2) to speculate as to how the criteria may change in the immediate future, 3) to convey the point that seismic criteria for NECs may have to evolve due to the magnitude of capital, generating capacity, and the safety problems involved, and 4) to identify techniques and tools that may be available to guide the drafting of and the compliance with the future seismic criteria with special emphasis on Nuclear Energy Centers.

No attempt has been made to speculate on specific siting or operating criteria or to prioritize the identified list of methods and hardware that could potentially be implemented to meet such criteria. Some form of screening based on cost/benefit analyses, availability, proprietary nature, and overall verification and credibility would be a logical extension of this study.

This section is devoted to: 1) summarizing changes in seismic input, soil structure interaction, and structural analysis that in the opinion of the authors will be evaluated for incorporation into seismic criteria guidelines, 2) delineating some additional areas that might be reviewed, and 3) recommending logical extensions of this study.

ANTICIPATED CRITERIA CHANGES

Criteria changes are anticipated in seismic input, soil structure interactions, and structural analysis.

Seismic Input

Increasing the SSE and OBE will have an obvious impact on construction cost in some parts of the country, especially in the East. The need to increase the levels has not been absolutely demonstrated, and is based primarily on intuition. Ideally, such an increase should be based on

careful risk analysis such as those developed by using the techniques of Cornell (Cornell, 1968) or Nair (Nair, 1976).

Site-dependent spectra and site specific earthquake approaches will require confirmatory research to provide a sufficient technical basis to justify a Regulation Guide. The best known researcher in this area is M. Trifunac (1974), who has strongly and repeatedly advocated the use of an input design spectrum that was more dependent on the source mechanism and travel path history. The basic problem is an inadequate data base of strong motion records for many parts of the country, particularly for large earthquakes. The costs of implementation of site-specific earthquake techniques will probably not be a major factor since it replaces many elements in the conventional design chain (site response, alternative studies, statistical and probabilistic analyses). The method has undergone a reasonable degree of verification and is being extended for specific NRC review. These changes relate to singular plants as well as NECs; however, the unique aspects of NECs may accelerate their evaluation and implementation.

Soil-Structure Interaction

There should be a substantial effort to develop improved site response methods especially for NECs, considering the relatively large areas involved. Here, however, there are real interface problems. The entire regulatory process is built around the concept of deconvolution. Because deconvolution requires Fourier superposition, the soil mechanical properties must be linear. The method that Professor Seed has developed (Schnabel, Lysmer, and Seed, 1972) iterates elastic solutions to achieve an equivalent-linear solution to the non-linear response. All this is to say that, technical merits aside, we may be designing with deconvolution techniques for quite awhile. It would be prudent, therefore, to elevate the equivalent linear method to the most sophisticated position possible. One improvement that would significantly add to the credibility of the method would be the inclusion of a better hysteretic damping model. Such a model is not being worked on, but if it were available, it would improve the site response calculations with no cost or interface difficulties.

With regard to synthetic accelerograms, the concept is straightforward and the tools are available (Trifunac, 1971; Donovan, 1973). Once the need for several accelerograms is demonstrated, the policy will follow shortly. The costs and interface difficulties are negligible, but some of the codes for generating the accelerograms are proprietary. A sufficient number of these codes are in the public sector, however, so that this is a minor problem.

Shannon and Wilson, Inc. (Shannon and Wilson, 1976) has devoted a great deal of effort to developing reliable in-situ measuring devices. Such devices could result in slightly higher exploration costs, but savings would probably result elsewhere (for example, laboratory testing). A logging or measuring device could very likely be developed in this area.

The traveling wave problem may result in the development of appropriate techniques, and the problem is sufficiently simple that several alternatives should be provided. Lawrence Livermore Laboratory is currently interested in the problem and has recently summarized their perspective of the issues (Bernreuter, 1977). Possible traveling wave criteria could impact other seismic criteria, i.e., the deconvolution. Also difficulties would arise in regulating a partitioning of energy between traveling and vertically incident. Despite these difficulties, traveling waves will be considered, at least informally, in licensing applications. There would probably be some small additional costs associated with implementation of such criteria.

The two-dimensional/three-dimensional modeling difficulties are presently being researched by Professor Lysmer and his colleagues. Their efforts or variations thereof will almost certainly be incorporated into licensing policy. Their methods are non-proprietary and the only cost is the additional computer time required for solution.

Structural Analysis

There would be negligible impact on the licensing process if modeling constraints were laid out with regard to torsion. Most computer codes

readily accommodate that degree of freedom, the additional costs are negligible and the only extra effort is in modeling.

ADDITIONAL AREAS FOR REVIEW

A great deal of emphasis has been placed on the unique nature of nuclear energy centers; i.e., centralization of large capital expenditures, generating capacity, and nuclide and waste inventory. It is the opinion of the authors that sponsors of an NEC will welcome any improvements in seismic risk analysis. Many individuals, not the least of which the NRC staff, have identified areas in the criteria that could be improved if the appropriate technology were available and adequately verified. It may well be that the unique nature of NEC coupled with the long lead time associated with NEC acceptance and implementation may enable criterial development to encompass potential improvements in our technology. This has already been intimated in the discussion on site-specific earthquakes and earthquake prediction. The intent of this summary is not to criticize existing procedures but merely to illuminate areas that given technological advancement might be amended or appended to future criteria for Nuclear Energy Centers. These discussions will necessarily be brief.

Seismic Input

Some concern has been voiced as to the definition of a capable fault. Geology is evolving from an art into a science and as this progresses, our understanding of tectonics and associated seismicity improves. It is hoped that additional research efforts will result in a better understanding of faulting and its impact on surface facilities. Similarly as our understanding of intermediate to deep earthquake mechanisms and their relationships to fault motion improves this may be reflected in the criteria for NECs. Unfortunately this is a difficult and time-consuming effort.

A second area of concern is with the lack of correlation between seismological parameters such as intensity-acceleration data. There are

numerous reasons for this lack of correlation: 1) the quality of building construction varies widely; 2) the frequency content of the ground motion relative to the natural periods of the structures affected causes considerably different structural amplification factors over the peak ground acceleration; 3) large and small earthquakes are intermixed; and 4) a wide range of epicentral distances are used in the correlations. Obviously the paucity of data is the culprit in this case. As the data base grows so will the empirical correlations. It is anticipated that given adequate research support, the relationships required by regulatory agencies to draft criteria will be improved by the time an NEC is licensed.

Site Response/Soil-Structure Interaction

Five major areas will be addressed in this section. Once again it must be stated that these problem areas are not the result of lack of objectivity on anyone's part but merely from a lack of reasonable alternatives that have been adequately verified. It is hoped that additional effort in these areas will be productive and that NEC criteria will parallel any results.

The first concern relates to the soil measurements and modeling. The input required from an analyst is shear modulus (G) and damping factor (Δ) as a function of average strain, density, and Poisson's ratio for each significant layer above bedrock. Currently, the lack of in-situ measuring devices dictates that the information be generated in laboratory tests on cores. This results in uncertain estimates of average shear strain throughout the core, potentially large errors due to core sample disturbance and sample size effects, and tensional and compressional symmetry in strain-dependent soil properties. Thus the mathematical formulation allows the soil to not only push the structures, but to pull them as well. To circumvent this problem the regulations have had the insight to stipulate that the foundational level spectrum be derived from three separate soil response calculations to encompass possible minimum and maximum variations. It is interesting to note that this results in effectively increasing the surface design spectrum. It is anticipated that improvements in in-situ measuring

capabilities may preclude this procedure and the conclusion is that this is one very important applied research area.

Another problem relates to site modeling based on borehole logs which delineate the stratigraphy. Some flexibility exists in the choice of a model and the characteristics of bedrock which can have a profound effect on final design parameters. It is hoped that criteria for an NEC would circumvent any non-uniqueness presented here.

Another concern is the conversion of seismic response spectra into acceleration time histories. There are two major assumptions involved. First, there is a 0.1% damped response spectrum associated with the Fourier spectrum. This relation is tenuous, and the effects of a non-zero damped spectrum are not well understood. A second, and more important, assumption is that the spectral amplitudes control the soil structure interaction response and the phasing of the individual frequencies is random in nature. Thus, there is an infinite set of time histories that could represent a target spectrum. If phases were deemed an important parameter, it would be necessary to know the sensitivity of the system response. Additional work should be performed concerning the sensitivity to the particular phase spectrum prior to drafting NEC criteria.

Finally, the equivalent linear method (ELM) is a major concern because of a lack of verification with real data, the basis of damping formulation and its extrapolation to strong motion earthquakes, and the statistical smoothing associated with superposition of multiple records. Obviously the NRC recognizes these concerns as they have required that the foundation level spectrum be not less than 60% of the surface spectrum. However, for NEC criteria, additional work would be advisable.

Structural Analysis

Because the technology of structural analysis is extremely advanced relative to seismic risk analysis and soil-structure interaction, it is difficult to define areas where the advent of an NEC would change criteria.

However, one area that may deserve some additional effort is in the combination of loads. This occurs at two levels. First, the net earthquake load must be characterized, and this involves either combining individual structural loads from each of the three earthquake components or combining the three components vectorally and performing a more complex three-dimensional structural analysis. Whichever approach is taken requires a decision as to the orientation of the incoming seismic energy relative to the structure. This may force criteria as to facility spacing. Second, the NRC requires that the seismic loads be combined with operating loads, transient loads, and abnormal loads. The manner in which all these loads are combined determines the final design loads on the structure and equipment and thus can be considered the bottom line criteria.

RECOMMENDED STUDY EXTENSIONS

This study is designed to be preliminary and educational in nature. Such a composite description of existing procedure is not currently in print to our knowledge. However, recommendations as to an extension of this study appear appropriate. Therefore, the following areas are presented for evaluation:

- 1) Development of hypothetical criteria for an NEC and a program to meet such criteria using Hanford as a test case.
- 2) Prioritization, cost/benefit analysis, and availability screening of the identified tools and procedures
- 3) Implementation of one or more of the most dramatic techniques such as site-specific earthquakes using Hanford as the test case.

The site-specific element should be noted since we are of the opinion that any additional meaningful work under Items 2 and 3 must necessarily be site specific.

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APPENDIX A
BACKGROUND, REGULATORY GUIDES AND STANDARDS

APPENDIX A

BACKGROUND, REGULATORY GUIDES AND STANDARDS

(Adapted from ASCE Manual, Ref. A-7)

A.1 BACKGROUND INFORMATION

The requirements governing nuclear power plant design generally paralleled conventional design requirements until the early 1960's. Beginning about 1965 the Regulatory Division of the Atomic Energy Commission (now NRC), in their review and approval of the Preliminary Safety Analysis Reports (PSAR) required considerably more detail. The Commission also began to require evaluation of extreme loads. In addition, the efforts on the ASME Boiler and Pressure Vessel Code Section III and the Joint ACI-ASME Committee on concrete containments and pressure retaining components and the standards development efforts of the American Nuclear Society (ANS), and the American National Standards Institute (ANSI) as a coordinating agency, all combined to develop over the past 12 years a large quantity of new design criteria applicable to nuclear design. This development has proceeded to the point where there are over 75 different documents prepared by a variety of industrial and regulatory groups in the U.S. which have a direct bearing on safety related structural design and analysis.

A.2 PHILOSOPHY OF PROTECTION AGAINST NORMAL AND EXTREME LOADS

Nuclear structural design requirements are to a considerable degree unique. In no other structural system are extreme loads such as tornadoes, earthquakes effects, etc., typically in excess of any recorded historical data at a site, and postulated accidents down to the 10^{-7} probability range explicitly considered in design. The consideration of extreme loads of such low probability is warranted by the potential consequences of accidents associated with nuclear facilities (Ref. A-3). As a result, a much broader spectrum of extreme loads are considered in design of nuclear facilities compared to conventional ones.

It also should be understood that the overall reliability of a structural system is not only a function of the applied loads but also the reliability of the structural response of the structure to that load. The quality assurance programs for the design and construction of conventional building structures typically have been based on informal or "in house" procedures which rely heavily on the integrity and competence of first line supervision. In such structures quality control has for the most part been based on visual inspection. Such procedures are in contrast to pressure vessel quality assurance and control procedures which require extensive audits, approval of quality assurance procedure, and third party inspection of quality control tests which include radiography, ultrasonic testing, dye penetrant and magnetic particle testing of as-built components. To a large extent many of the quality assurance and quality control measures traditionally used in pressure vessel design are now applied to concrete and steel safety class structures.

The risk associated with the occurrence of a particular event in its most simplistic form is the product of the probability of occurrence of the event and the consequences of the event. For a desired risk level, as the probability of occurrence of an event decreases, the consequences may be allowed to increase. Thus increase in consequences in structural design may be associated with reduced safety margins in design of structures for low probability events.

Central to this extreme load design philosophy is the reduction of structural safety factors as the probability of load occurrence is reduced. This requires that the response of structures to extreme loads must be predicted with a higher degree of confidence than is typically the case with conventional structures. As a result, quality control and quality assurance requirements are considerably more stringent than for conventional structures, and nonconventional analytical qualification may be required.

A.3 GENERAL CONSIDERATION IN DESIGN AND SAFETY CATEGORIZATION OF STRUCTURES

The specialized requirement of structural design and analysis presented in this Manual are applicable to "Safety Class Structures." This section presents various safety classifications typically used to describe the safety classifications of structures, mechanical and electrical components (Ref. A-4).

The use of Safety Classes established by ASME and ANS standards should not be confused with the Seismic Category I classification established by Federal Regulation 10CFR100 Appendix A and further defined by the NRC in R.G. 1.29. In general the NRC Seismic Category I applies to all structure systems and components "important to safety" which must remain functional in the event of an SSE. "Important to safety" is further defined by the NRC as those structures, systems, and components whose function is to assure: (1) the integrity of the reactor coolant pressure boundary, (2) the capability to shut down the reactor and maintain it in a safe shut-down condition, or (3) the capability to prevent or mitigate the consequences of accidents which could result in offsite exposures comparable to the guideline exposures of 10CFR100. Because the safety classification of structures, systems and components defined by the NRC is restricted to earthquakes, there is a tendency to use the industry safety classifications.

For structures, systems and components important to safety, five safety classifications are defined; two general classifications without gradation, one for structures and one for electrical systems and components, and three graded safety classes for mechanical systems and components.

Structures, systems and components that are categorized in the five safety classes are designed to remain functional during all design basis events, unless it can be demonstrated that the structures, systems and components will not be required to perform their safety function during such events or that such events are precluded from interacting on the structure, system or component by an isolation or barrier system. Safety class structures, systems and components are subject to the Quality

Assurance requirements of Federal Regulations (Ref. A-5). Structures, systems and components not considered important to safety are designed Non-Nuclear Safety (NNS) and in general are designed to meet conventional requirements.

The failure of any NNS structure, system or component may not lead to loss of function of any safety class structure, system or component.

A.4 SUMMARY OF EXISTING CODES, STANDARDS AND REGULATIONS

This section is presented to assist determining the sources of design criteria required for nuclear power plants. The role and purpose of various agencies, codes and standards groups are briefly discussed and references to source material presented.

A.4.1 Summary of Current AEC, ASME, ACI, ANS, ACI-ASME and IEEE Seismic Standards

Figure A-1 is a summary of the current codes, standards, and criteria generally applicable to the seismic design and analysis of nuclear facilities. Not included but playing an important role is the American National Standards Institute (ANSI). Through its technical society representation of the Nuclear Technical Management Board, ANSI determines the needs for, assigns, and schedules the development of standards. Many standards developed by sponsoring organizations also carry ANSI designations. Where such designations are identified the corresponding ANSI designation is shown parenthetically. Reference A-6 contains a list of nuclear standards under the auspices of ANSI.

A.4.2 Federal Regulations

The most important of the NRC documents in the structural area are Federal Regulations 10CFR100 Appendix A and 10CFR50 Appendices A and B. These documents have the weight of Federal law to require compliance.

A.4.2.1 10 CFR 100 Appendix A

This document defines the OBE SEE and the way their intensities are determined. It also locates where the earthquake motion is defined and sets the width of fault zones as a function of fault length and defines capable and noncapable faults.

NRC	ANS-ANSI	ASCE-AISC	ASME-ACI	IEEE
10 CFR 100 Appendix A	ANS 2.1 Guidelines for Determining the Vibratory Ground Design Earthquake	TG3-Land and Behavior Criteria	N-166-Seismic Qualifications for Nuclear Power Plant Structures Equipment	344-Guide for Seismic Qualification of Class 1 Electrical Equipment for Nuclear Power
10 CFR 50 Regulatory Guides	ANS 2.2 Earthquake Instru- mentation Criteria for Nuclear Power Plants	TG6-Seismic Design Impact and Impulse Design	N-167-Seismic Analysis of Category 1 Structures, Systems and Components	
Regulatory Guide 1.12 Instrumentation for Earthquakes (Revision 1, 4/74)	ANS 2.7 Earthquake Fault Criteria for Loca- tion of Power Reactor Sites	TG9-Structural Aspects of Nuclear Plant Siting -Surface Plants -Floating Plant -Underground Plants	N-249-Combination of Loadings for the Design of Component Supports Under Upset, Emergency and Faulted Plant Conditions	
Regulatory Guide 1.29 Seismic Design Classification (Revi- sion 1, 8/73)	ANS 2.10 Guidelines for Use of Data Obtained from Earthquake Instrumentation	N175-Geological Design Criteria	N-250-Combination of Loadings for the Design of Category 1 Mechanical Components Under Upset, Emergency and Faulted Plant Conditions	
Regulatory Guide 1.60 Design Response Spectra for Seismic Design of Nuclear Power Plants (Revi- sion 1, 12/73)	ANS 2.11 Guidelines for Deter- mining Geological Information at Power Reactor Sites		N-252-Combination of Loadings for the Design of Fluid System Compo- nents Under Upset, Emer- gency and Faulted Plant Conditions	
Regulatory Guide 1.61 Damping Values for Seismic Design of Nuclear Power Plants (10/73)	ANS 2.12 Combined Natural and Manmade Hazards			
Regulatory Guide 1.70.9 Additional Information Design of Seismic Category 1 Structures (11/74)				
Regulatory Guide 1.70.23 Information for Safety Analysis Reports - Seismic Qualification of Instrumentation and Electrical Equip- ment (2/75)				
Regulatory Guide 1.92 Combination of Modes and Spatial Components in Seismic Response Analysis (12/74)				
Standard Review Plan SRP 2.5 Geology and Seismology				
SRP 3.6 Seismic Design				

FIGURE A-1. Index of Current Codes, Standards and Criteria Applicable to Seismic Design

A.4.2.2 10 CFR 50 Appendix A

This document defines General Design Criteria to be used in the design of safety class nuclear plant facilities. It contains the following criteria of particular interest:

- Criterion 1 - Quality Standards and Records
- Criterion 2 - Design Bases for Protection Against Natural Phenomena
- Criterion 4 - Environmental and Missile Design Bases
- Criterion 16 - Containment Design
- Criterion 50 - Containment Design Bases
- Criterion 53 - Provisions for Containment Testing

A.4.2.3 10 CFR 50 Appendix B

This document describes the quality assurance criteria for nuclear power and fuel reprocessing plants. It is divided into the following areas:

1. Organization
2. Quality Assurance Program
3. Design Control
4. Procurement Document Control
5. Instructions, Procedures and Drawings
6. Document Control
7. Control of Purchased Material, Equipment and Services
8. Identification and Control of Materials Parts and Components
9. Control of Special Processes
10. Inspection
11. Test Control
12. Control of Measuring and Test Equipment
13. Handling, Storage and Shipping
14. Inspection, Test and Operating Status
15. Nonconforming Materials, Parts or Components
16. Corrective Action

17. Quality Assurance Records

18. Audits

A.4.3 NRC Regulatory Guides

Regulatory Guides are prepared by the NRC Division of Regulatory Standards and are issued to describe methods acceptable to the NRC Regulatory staff, delineate techniques used by the staff in evaluating specific problems or postulated accidents, or provide guidance to applicants. Regulatory Guides are not regulations and compliance with them is not required. Methods different from those in the guides are acceptable if they provide a basis for the findings requisite to the issuance or continuance of a permit or license.

Guides are issued in the following divisions:

1. Power Reactors
2. Research and Test Reactors
3. Fuels and Materials Facilities
4. Environmental and Siting
5. Materials and Plant Protection
6. Products
7. Transportation
8. Occupational Health
9. Antitrust Review
10. General

In the following paragraphs a brief description of those Regulatory Guides of particular interest to the Civil-Structural Engineer is presented.

A.4.3.1 R.G. 1.12 - Instrumentation for Earthquakes

This guide defines the instrumentation required to record the effects of earthquakes.

A.4.3.2 R.G. 1.29 - Seismic Design Classification

This guide defines those systems and components which require verification of seismic design adequacy. Such seismic design adequacy is required to assure (1) the integrity of the reactor coolant pressure boundary,

(2) the capacity to shut down the reactor and maintain it in a safe shut-down condition, (3) prevent or mitigate consequences of accidents which could result in radiation release in excess of 10 CFR Part 100 guideline exposures.

A.4.3.3 R.G. 1.60 Design Response Spectra for Seismic Design of Nuclear Power Plants

This guide establishes the ground response spectra which will be used to seismically qualify structures located at ground and to qualify time history input motion which are used to develop amplified spectra for use in design of components located within building structure. Horizontal as well as vertical spectra are specified.

A.4.3.3 R.G. 1.61 - Damping Values for Seismic Design of Nuclear Power Plants

This guide presents interim modal damping values which are currently acceptable to the NRC. Values are tabulated for both the OBE and SSE and different structures, systems, and components.

A.4.3.5 R.G. 1.70 - Standard Format and Content of Safety Analysis Report for Nuclear Power Plants - LWR Edition

This document identifies the principal information that should be provided by applicants in safety analysis reports for light-water-cooled reactors and defines a uniform format for the information. The Standard Format was developed in parallel with and is keyed to the Standard Review Plans prepared by the NRC Office of Nuclear Reactor Regulation.

A.4.3.6 R.G. 1.91 - Evaluation of Explosions Postulated to Occur on Transportation Routes Near Nuclear Power Plant Sites

This guide describes a method acceptable to the NRC Regulatory staff for determining safe distances from a nuclear power plant to a transportation route over which explosive material may be carried. It also provides data for the development of peak positive overpressure associated with accidental explosions as a function of distance and equivalent TNT charge.

A.4.3.7 R.G. 1.92 - Combination of Modes and Spatial Components in Seismic Response Analysis

This guide provides a suggested method for combining seismic response effects between modes including closely spaced modes as well as spatial combinations considering independence of directional components of the earthquake.

A.4.4 NRC STANDARD REVIEW PLANS, SRP

Regulatory Standard Review Plans are prepared for the guidance of the NRC Directorate of Licensing staff responsible for the review of applications to construct and operate nuclear power plants. These documents are made available as part of the Commission's policy to inform the nuclear industry and the general public of staff scope and policies on Safety Analysis Reports. Standard Review Plans are not substitutes for Regulatory Guides or Federal Regulations and compliance with them is not required. Standard Review Plan sections are keyed to the Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants, R.G. 1.70. Not all sections of the Standard Format have a corresponding review plan.

The Standard Review Plans in general incorporate requirements of "Branch Position Papers" which in the past were informally issued for guidance in the preparation of Safety Analysis Reports.

A.4.5 AMERICAN NUCLEAR SOCIETY, ANS

The American Nuclear Society (ANS) typically prepares systems or functionality standards on nuclear plant design while ASME, ACI, etc., typically prepare hardware standards on the detailed design and stress or behavior analysis of specific components.

A.4.5.1 ANS-2 - Site Criteria

The ANS-2 committee covers the criteria which affect the plant and have their basis in natural phenomena. A list of guidelines prepared by this group is shown in Figure A-1.

A.4.5.2 ANS-50 - Reactor System Safety Criteria

The second major ANS committee activity develops the safety criteria for the design of the four major nuclear reactor types used in the U.S., i.e., Pressurized Water Reactors, Boiling Water Reactors, Gas Cooled Reactors, and Sodium Cooled Fast Breeder Reactors. In addition to the four major subgroups on each reactor type this committee is concerned with the plant process conditions of design and their load combinations including interaction with natural phenomena and the associated operating or design condition criteria and the safety classification of components. This committee also has two subcommittees developing missile and pipe whip and high energy fluid jet effects design criteria.

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(A revision is due soon.)

APPENDIX B
THREE-DIMENSIONAL FAULT MODEL

APPENDIX B

THREE-DIMENSIONAL FAULT MODEL

B.1 TECHNIQUE VERIFICATION

The value of numerical computer methods for modeling earthquakes hinges on demonstrated credibility. Consequently, considerable effort has been devoted to testing and verifying the various methods that are used.

On the most elementary level, the accuracy of the numerical scheme has been examined for propagating waves in a homogeneous medium. The conclusion is that, in the absence of material viscosity, waves travel slower in the finite element grid than in the continuous medium. This numerical dispersion is dependent on the number of element dimensions per wave length. For wavelengths longer than six grid dimensions, the reduction in the propagation velocity of numerical waves is very insignificant and does not exceed 4%.

The method for numerically simulating fault slip has been tested and verified in several ways: The first test was to numerically reproduce analytical results for a growing surface of dislocation in a full space. Excellent results have been reported by Geller and Frazier (1974) and more recently by Geller and Frazier (1976) using the SWIS code to model a propagating dislocation acting in a 2-D plane strain. The slip model has also been verified in 3-D by comparing with analytical results.

Numerical simulations for propagating dislocations serve to verify the computer methods that are used for modeling slip. However, additional tests are needed to substantiate the computer models for simulating stress drop on a growing crack. This process is verified by numerically reproducing analytical results for the problem of a growing circular crack in a pre-stressed medium (Kostrov, 1964; Burridge and Willis, 1969; Richards, 1973). The particle displacement that results from an instantaneous drop in shear stress is presented in Figure B-1 at various points along the path of rupture, which is expanding at 0.98. Whereas the analytic solution applies for a self-similar crack that expands at a constant rupture velocity forever, the 3-D finite element code was used to simulate a circular crack that starts at a point, grows to a radius of ten element dimensions at a constant

rupture velocity, and then stops. The material was healed in a finite element model when the slip attempted to reverse directions.

The accuracy that is achieved using 3-D brick elements is remarkable. Particle velocity is infinite immediately following rupture in this idealized model. Yet, the finite element model produces particle displacements that jump, with no apparent oscillation, to the analytical values in a single time step (the symbols +, in Figure B-1 designate the individual time steps of the SWIS code).

Several other calculations have been performed to demonstrate the capabilities of the SWIS code for propagation P-waves, S-waves, and surface waves. More important, at this point, is the suitability of the computer methods for simulating physical rupture.

B.2 STRIKE-SLIP CALCULATIONS

Having verified the finite element code as a positive approach to simulating propagating ruptures, we have also compared finite element results with the laboratory results obtained by Archuleta and Brune (1975). First though, a finite element solution to a bilaterally propagating stress drop over a semicircular plane embedded in a homogeneous, isotropic, elastic, half-space will be described. A cross section of that medium is shown in Figure B-2. The rupture originates at the free surface at the center of the semicircular arc and then propagates as a semicircular wavefront which has a speed of 0.9 of the shear wave speed. The fault plane is limited to a radius of 10 elements. Because of the symmetry of the displacement field and because the rupture is bilateral, only one quadrant of the half-space V is needed to grid. Thus, Figure B-2 shows twice as much grid as actually used. (As a matter of notation, the direction of the shear has been specified as the Y_1 direction; the direction normal to the free surface and towards increasing depth as Y_2 , and the direction perpendicular to the plane of the fault Y_3 which form a right-handed system.) Figures B-3 and B-4 show the development of the horizontal particle velocity field on the free surface as the free surface as the rupture propagates and stops. The vector sum of the $\dot{u}_1$ and $\dot{u}_3$ for all four quadrants is plotted where the dot denotes a time

FIGURE B-1. Displacements on a Circular Fault Growing at 0.9β . Dashes are three-dimensional finite element results for fault which stops growing at radius r . Solid lines are Kostrov's analytic solution for circular fault which doesn't stop.

FIGURE B-2. Cross-section of a Half-Space Illustrating Finite Element Grid Used for Three-dimensional Run in Which Semicircular Fault had 10 Elements on a Radius

FIGURE B-3. Horizontal Particle Velocity Field on the Free Surface at Four Instants in Time During a Three-dimensional Simulated Earthquake

5 sec

6 sec

FIGURE B-4. Same as B-3 (except only two instants in time are shown)

derivative. The heavy dark line extends around the border of the rupture. One can see the compressional and shear lobes of the classical double couple radiation field; the propagation of waves from the ends of the fault. On a larger scale, one can discern the propagation of the near-field transverse motion propagating at the P-wave speed. Figure B-5 shows in greater detail the time histories of displacement and velocity of nodes 1-11. The nodes lie right on the fault trace at the free surface. Node 1 is at the origin (0, 0, 0), node 2 is at (1, 0, 0), node 3 is at (2, 0, 0), etc. The particle velocities illustrate more clearly the dynamics occurring as the rupture propagates and stops. First, all components of particle velocity exhibit an amplification as the rupture propagates. Secondly, the vertical ($\dot{u}_2$) component is comparable to the transverse component ($\dot{u}_3$). An interesting phenomenon can be seen most easily in $\dot{u}_3$. (This phase is the emerging long-period signal clearly seen at nodes 2-6.) The second part of the stopping phase propagates from node 1 out through the other nodes. This occurs because now the node at the origin has locked which generates this wave. (This wave is seen as the trough of the long-period wave most clearly visualized in $\dot{u}_3$ around nodes 2-6.) In addition to saving time histories of selected positions plus the time history of every point on the fault, we also calculate and save the maximum horizontal and vertical particle velocity and displacements everywhere on the free surface. A contour plot of the distribution of maximum horizontal particle velocity is displayed in Figure B-6. The fault region is magnified and have plotted all four quadrants. The contours are labeled A-1. The number in parenthesis is the value of the particle velocity in cm/sec if the fault radius were equal to 10 km and had a stress drop of 100 bars, e.g., B(200) means that contour is for 200 cm/sec. For the most part, the area within one fault radius has peak particle velocities greater than or equal to 15 cm/sec. Quite striking are the high values of particle velocities in the two-lobed triangular region near the fault trace.

Figure B-7 shows results obtained from a finite element run in an attempt to match displacement time histories measured by Archuleta and Brune (1975). Because this rupture was not bilateral, two quadrants of a half-space were used in this run. The fault plane is semicircular, but

FIGURE B-5. Particle Displacements and Velocities for Points on the Fault Trace at the Free Surface

FIGURE B-6. Contour Map of Maximum Horizontal Particle Velocity on the Free Surface of a Three-Dimensional Element Simulation of a Bilaterally Propagating Rupture

COMPARISON OF DISPLACEMENTS
FROM FOAM EXPERIMENT (Δ) AND FINITE ELEMENT CODE (-)

FIGURE B-7. Comparison of Three-dimensional Finite Element Displacements Generated by a Unilaterally Propagating Rupture Against Foam Rubber Displacement Data

only four elements on a radius were used instead of 10 used in the run discussed above. Rupture velocity was set at 0.74 of the shear wave speed. The match between static amplitudes is close. The rise time of the foam rubber displacements are initially comparable to the finite element result, but the overall rise time in the foam rubber model is slower. This difference which may stem from several causes, e.g., lack of uniform, prestress in the foam rubber or time-dependent friction is not completely resolved.

B.3 RUPTURE MODELING

Rupture modeling in the finite element work is based on the widely accepted "stick-slip" concept of frictional instability (Brace and Byerlee, 1966; Byerlee, 1970; Byerlee and Brace, 1968; Scholz, et al., 1972). Basically, the concept of the stick-slip model is that rupture initiates at a point when the shear stress exceeds a critical value τ_k which is a function of the material strength and the stress component acting normal to the fault plane. When this critical state of stress is reached, the material rapidly loses some of its capacity for supporting shear, and consequently, the shear stress drops from τ_k to a lower value τ_f which is rather insensitive of the rate at which local processes (material alterations) occur. Material on the opposing faces of the fault begins to slide in the direction of the stress drop $\tau_k - \tau_f$ as a result of the imbalance that is created. The readjustment of material on a macroscopic scale accentuates the state of stress in any adjacent material that has not yet ruptured, and in this way the zone of rupture spreads. As the sliding and the locally stored strain energy is relieved, sliding decelerates due to opposing friction stress. At the instant the slip velocity reverses direction, shear stress drops below the shear carrying capacity of the material during sliding, τ_f . At this point, microscopic failure processes are no longer exceeded, and the fault material appears to heal. Additional stick-slip failure can occur only if the shear stress exceeds the initial value τ_k or some modified value slightly less than τ_k .

The failure process currently operating in the finite element code differs from the stick-slip model in one important respect: The onset of rupture is not determined from a failure criterion but rather from a

prescribed velocity. That is, the rate at which the rupture spreads into competent material is prescribed. This procedure has been adopted in the initial work to insure that the grid size does not have an undesirable influence on the rupture model. A new method based on fracture energy for spontaneously initiating new crack surface also has developed. It appears that the use of fracture energy as a criterion for creating new crack surface is far superior to stress criteria which depend rather strongly on grid size. However, it is intended to continue to prescribe rupture velocity until a spontaneous rupture model is developed which is insensitive to grid size.

The three-dimensional computer model has considerable flexibility for including complexities, such as rate-dependent effects that may arise during actual earthquakes.

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