

## Seismic Design Guidelines for Existing Nuclear Power Facilities in Light of an Expanding Database of Knowledge

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There has been a significant evolution of seismic design criteria for nuclear power plants over a twenty-five year period since the first commercial facilities were designed. Three phases of evolution seem to have developed that are leading to technical approaches believed to be more realistic in light of current knowledge:

1. Recognition by regulatory authorities and owners of the need to apply more rigorous attention to the seismic safety of critical facilities,
2. Development of seismic design criteria and methodologies, and
3. Reconciliation of an expanding database of new information with the existing seismic design criteria and methodologies for the formulation of improved guidelines for the evaluation of new and existing facilities.

The most pronounced proliferation of seismic design criteria surfaced in the period between the mid sixties and the mid seventies. These criteria evolved without benefit of sufficient real data; yet, for the most part, when properly implemented, the resulting designs appear to possess adequate safety margins when measured against our expanding knowledge which has developed significantly over the last several years. The guidelines embodied in "current" criteria have often resulted in costly, and in general, overly conservative designs with a trend towards stiffer, stronger and possibly less ductile facilities. However, these criteria have sometimes compounded negatively leading earthquake engineers to question issues such as the capability of engineered facilities to resist a range of earthquakes, the effects of restraints on normal operations, inspectability and continued functionality with age.

While improvements to current criteria may be desirable, the "intent" and general level of safety that these criteria dictate as a "package" should be preserved. Seismic resistance does not imply a total absence of limited permanent deformation. Certain structures, piping, and equipment may suffer damage provided functional requirements are met and the plant is able to achieve and maintain a safe shutdown condition. Therefore, the reevaluation of existing facilities requires an assessment of broad safety issues considering the various systems interactions and potential accident sequences in the context of overall plant safety.

New information, both empirical (i.e. real earthquake data describing ground motion and structural performance) experimental, and analytical has surfaced as a direct result of recent earthquakes and governmental funded research.

In consideration of this information and the authors experience in the evaluation of older nuclear power plants, the rationale for seismic reevaluation guidelines for existing nuclear power facilities is discussed. These guidelines recognize and attempt to deal with the inherent and often unquantifiable capability of existing facilities to resist seismic forces and deformations and the conservatism associated with current evaluation methods.

## 1. Introduction

The earliest nuclear power plant facilities were designed and constructed with little or no specialized attention to seismic design considerations as well as hazards from other extreme external phenomena. These facilities were most generally designed to provisions of building codes commonly used for conventional facilities. An expanding database of knowledge from later investigations, experiments and observations have generally demonstrated significant seismic resistance capability of these facilities; however, to a large degree this capability is unquantified.

Regulatory authorities and owners soon recognized the special safety problems that earthquakes may pose to these critical facilities, which might possibly lead to a release of fission products. The ensuing promulgation of seismic design requirements for new facilities is well documented, leading to the publication of the Nuclear Regulatory Commission's (NRC) Standard Review Plan (SRP) in 1975 which was later updated in 1981.

Virtually all of the U.S. nuclear power plants operating today have been designed to different criteria than is embodied within the current SRP. Recognizing the rapid evolution of many design criteria (including seismic design criteria), and the fact that the design bases of early facilities was not as well documented as today, the NRC initiated the Systematic Evaluation Program in 1977 to reassess the safety of older operating nuclear power plants. While the SEP program (which is still ongoing) has as its primary charter an integrated assessment of overall plant safety using current criteria as a yardstick, the program presented as a bi-product the first formalized opportunity for an introspective examination of the bases for today's criteria. Several significant items will be noted that have had a direct bearing on our understanding of seismic behavior and the development of a rational approach for seismic design guidelines for existing nuclear power plant facilities.

## 2. The Seismic Design Evolution

The development of seismic design guidelines for existing facilities requires knowledge of the seismic design evolution which has led to today's methodology as well as newly available information. While compliance with today's criteria may imply acceptability, this cannot generally be expected for older facilities in view the fact that these facilities were designed to varying design bases. Notwithstanding arguments of practicality of backfitting, in many instances demonstrating compliance with specific individual criteria may not be desirable when these criteria are considered outside the context of the total "package" of today's criteria. The current package of criteria, methodology and design chain has evolved into an overall design concept; one of many which would potentially satisfy the broader safety issues at hand. The design concept for reevaluation of older facilities more than often needs to differ; however the "intent" of current criteria must be maintained with respect to the general level of safety that these dictate.

The historic trend has been towards stiffer, stronger and possibly less ductile facilities. While today's designs may be perfectly adequate, earthquake engineers are now questioning aspects of today's methodology. In addition to the obvious economic impacts, technical issues such as the capability to resist a range of earthquakes, the effects of restraints on normal operations, inspectability, and continued functionality with age are under discussion. It is in recognition of these issues, how they evolved and newly acquired information, that seismic design guidelines for existing facilities have been developed.

Implicit in the seismic design provisions of building codes to which the earliest reactors were designed is the capability to resist minor to moderate earthquakes with little or no structural damage; however, for major or severe earthquakes structural damage would be expected, but life safety

maintained. The first rigorous attention to the nuclear seismic problem was not only concerned with the performance of structures, but with the integrity of the reactor coolant pressure boundary as well as other pressure boundaries of safety systems necessary to cool the reactor core. Consequently, deformation, strain and fatigue became important factors in assuring leak tight systems. Linear elastic, static and dynamic evaluation techniques were and still are commonly used for reasons of simplicity and practicality within the design office environment. Associated with these analytical techniques was the development of acceptance criteria (e.g. stress allowables) that when used as a package, largely dictated an overall elastic design. Superimposed within this evolving methodology was the general use of conservatively bounded parameters that were often utilized at each step in the seismic design methodology leading to an often unrealistic estimate of response (e.g. narrow banded, high amplitude response). While linear elastic techniques may be appropriate for the evaluation of selected components (e.g. dynamically sensitive active equipment that must change state during or after an earthquake) they have largely led to stiffer, stronger and less ductile structural/mechanical systems. These factors have shaped the way current plants are configured.

It is important to note that the earliest nuclear reactor facilities are generally less stiff and subject to larger relative deformations within the structures themselves. Provided that these facilities possess sufficient ductility, they may adequately survive earthquake motions as well. A body of new information to be discussed suggests that this may be the case. It follows that structures in the intermediate stiffness range require balanced strength and ductility.

The subject of functional equipment qualification has gained relatively recent attention insofar as its implementation on new reactor designs. Rigorous qualification by test was virtually non-existent prior to the early 1970s. The evolution of requirements in this area parallels that of areas previously discussed in that the overall methodology suffers from some of the same general problems. The greatest single issue centers around the demonstration of functionability and our capability to prescribe meaningful qualification tests serving as part of an overall systematic design process. The definitions of realistic functionability limits, the specification of required qualification motions with proper consideration of effective transmissibility functions for controlling motions between structure and equipment, as well as the duplication of this motion in the laboratory, poses special challenges. In addition to items previously cited, factors such as procedures for generating in-structure response spectra and decoupling have led to unrealistic response predictions, manifested in real physical changes to equipment. The use of these techniques involve considerable judgement in assessing the reasonableness of the peak response values and the frequency bandwidth of applicability. Multiple connections are especially troublesome to handle, irrespective of the technique employed.

The historical trend towards utilization of bounding and often conservative parameters is understandable in view of seismic design uncertainties. These uncertainties are perceived to be even larger when one attempts to specify a design basis earthquake. It has been customary to specify ground motion for the largest historical event occurring within the tectonic province that the reactor is sited. Decisions in this regard are often made in the absence of statistically significant real data. Over the years, as more data have been recorded, ground motion estimates have escalated significantly. For example, over the last 20 years, the peak ground acceleration (PGA) design levels for facilities in most regions of the U.S. have increased in amplitude. These higher levels have had a profound effect on new facilities and pose even more difficult prospects for re-evaluation of older facilities. While PGA has increased and the specification of magnitude is the subject of on-going studies, the representation of

the maximum design motion is of primary engineering concern. The focus of future research should be on a better understanding of the overall motion with emphasis on a definition of parameters important to engineered facilities versus attention to magnitude.

### 3. Our Expanding Database of Knowledge

Significant additional research is most definitely required to more accurately predict earthquake response of engineered facilities; however, our database of information has expanded exponentially in many areas, over the last decade due to increased research and the availability of real earthquake data, both measured and observed. This data has tended to confirm that the inherent seismic resistance capability of engineered facilities is greater than is assumed in past and current analysis and design methodologies. Thus, with improved knowledge relative to expected earthquake response of engineered facilities, it has become possible to examine our current methodology and develop guidelines for the evaluation of existing facilities.

New information in the following areas is believed to be most important:

1. Earthquake ground motion
2. Effective motion considerations (including resistance considerations)
3. Margins of safety - as inferred from more realistic evaluation of energy absorption mechanisms
4. Observations from real earthquakes - ground motion measurements, response of structures, systems and components
5. Response of equipment

#### 3.1 Earthquake Ground Motion

The first step in the seismic reevaluation of older facilities is an assessment of the adequacy of the seismic input originally specified for design. Our perceptions of the seismic hazard within various regions have changed in time, often requiring intensive reevaluation prior to embarking on an assessment of the facility's physical capabilities.

The current methodology for determination of design bases for vibratory ground motion as defined by 10 CFR 100, Appendix A, of the Regulations and the SRP utilize the generic Regulatory Guide 1.60 ground response spectra anchored at a zero-period PGA of the Safe Shutdown Earthquake (SSE). The PGA is established based upon required investigations of the local and regional geology, seismic history, and engineering characteristics of the site. These criteria in large part are deterministic and necessarily require bounding interpretations of important parameters. Generally, this procedure is believed to be adequately conservative; however, it has a tendency to produce variable estimates of the seismic hazard from site to site. The penalties associated with being overly conservative are particularly significant when reevaluating older facilities. Therefore, recognizing the inadequacies with the current approach, investigators from TERA Corporation have recently developed alternative approaches for the assessment of seismic hazard and the specification of ground motion parameters which are thought to be more realistic (1). These approaches include probabilistic seismic hazard analysis and source modeling methodologies which provide unique tools for decision making. Seismic hazard analysis is particularly interesting in that it allows:

1. Explicit tracking of important parameters and the sensitivity of their variance;
2. Quantification of predicted risk in a consistent and uniform manner;
3. Estimation of the relative risk from one seismic hazard level or design level to another, and;
4. Evaluation in a limited way of the required level of seismic resistance capability to meet overall risk goals.

Although seismic hazard analysis methods are controversial, particularly in estimating absolute levels of risk as implied in item 4, experience suggests their usefulness for the quantitative comparison of

relative risk as suggested in item 3. If properly used, this information is valuable in considering whether or not it is economically desirable or possible to backfit a facility to increase seismic safety margins.

The following approaches have been recently used for the evaluation of older operating reactor sites:

1. Direct statistical evaluation of response spectra from appropriate groups of real earthquakes;
2. Scaling of real spectra to peak acceleration values determined for various risk levels;
3. The Newmark-Hall technique of scaling response spectra to peak accelerations and velocities determined for various risk levels; and
4. Uniform risk technique—scaling spectral ordinates as a function of return period.
5. Source modeling of the earthquake rupture process, propagating seismic energy to the site for the determination of synthetic seismograms and response spectra.

### 3.2 Effective Motion Considerations

It is desirable to begin this discussion with some attention to structural resistance. Well designed and well constructed buildings have survived significant earthquake ground motion, even though most earthquake reconnaissance reports center around descriptions of damaged buildings and equipment. These studies of failures have been quite valuable and have contributed to the upgrading of earthquake engineering practice; however, surprisingly little attention has been devoted to detailed studies of lightly damaged or undamaged buildings and equipment, and the reasons for their survival. Earthquake damage reports suggest that the damage in well engineered buildings often does not correlate well with the observed PGA (2). Our base of knowledge for assessing the adequacy and margins of strength of structures and equipment must be improved in the years ahead through additional research involving studies of structural and mechanical systems that have not failed, as well as those that have failed. Even more importantly we need to define more explicitly what constitutes damage, and develop analytical/observational techniques for assessing and evaluating the various levels of damage from a practical point of view.

The instruments normally employed for making free-field ground motion measurements are strong motion accelerographs. Because acceleration is at least in part a measure of the force involved and because the zero period (high frequency) acceleration is commonly employed as the anchor point for design response spectra, it is natural that acceleration has been used so commonly as a descriptor of the ground motion. All three types of ground motion input (acceleration, velocity and displacement) are important and must be considered in an appropriate manner as part of the design process. However, one senses that there has been significant over attention given to acceleration, especially when considered in the context of the manner in which it is employed in the design of structural and mechanical systems and especially when one considers nonlinear behavior. In some respects velocity may be a better descriptor in that it is a measure of the energy involved in the response process, and may well be a better measure for assessing the parameters associated with the response and potential damage of a structure or equipment system. It is clear that spectra are not necessarily adequate indicators of energy input, number of cycles of significant motion and duration, all of which are important parameters in assessing damage potential. These topics are the subject of current research in terms of examining seismic input motion parameters, developing characteristic motion and response identification parameters, and in identifying the role of motion parameters as part of the resistance to excitation and in assessing structural damage levels.

Recent research as well as field observations, suggest that high-frequency spikes of acceleration do not have a significant influence in the response and behavior of mechanical and structural systems and that the repetitive shaking with strong energy content is the characteristic of the time history that leads to structural deformation and damage (3), (4). Obviously the nature of the motion (the loading) and the

response (as reflected in the properties and characteristics of the structure, the resistance) are clearly interrelated, and form the basis for the use of the term "effective motion".

With time it seems certain that velocity and displacement control values will assume increasingly important roles in defining relative spectral shape. Moreover, one can foresee where the concept of so-called "effective motion" will be broadened to include motions throughout the entire range of frequencies, energy input and capacity, as well as other input and response parameters. There are statistical and probabilistic aspects involved in effective motion tool, in the sense that no two earthquakes exhibit identical acceleration, velocity or displacement time histories or, identical response spectra, even at locations fairly close to each other. Similarly, there are uncertainties associated with the magnitude, which is a general measure of this overall energy input. Thus, the concept of effective motion must reflect the fact that for a given site and for possible earthquakes in a nearby region, the various sources of strong motion, the varying attenuation through the ground, the local site characteristics, and the nature and form of the structure and its resistance characteristics all have an influence on the motions that may be transmitted through the foundation.

### 3.3 Margins of Safety

The current evaluation techniques are sometimes unrealistic because certain energy dissipating mechanisms are not quantitatively considered. In considering the response of a structure to seismic motions, one must take account of various levels of deformation and damage, short of collapse, of the structure. Some structural elements must remain elastic or nearly elastic in order to perform their intended safety function. In many instances, however, a purely linear elastic analysis may be unreasonably conservative when one considers that, even up to a near yield point range, there are nonlinearities of sufficient amount to reduce required design force levels considerably. Nonlinearities below the threshold of overall elastic structural response have been found to lead to dissipation of significant energy.

Energy absorption below elastic limits is represented through structural damping, and hysteretic energy absorption. For convenience, structural damping is typically approximated assuming it is viscous/velocity dependent and is expressed as a percentage of critical damping. Structural damping represents a complex physical process that depends upon the properties of the material, the magnitude of internal and applied stress, the stress history and stress frequency. The geometric configuration, boundary conditions, joint slippage, gaps, friction, and yielding mechanisms play an important role.

Current regulatory guidance embodied in Regulatory Guide 1.61 present damping values which should be considered conservative lower bounds. These damping values are suitable for use in the design of new facilities in the absence of real data. Over the years, more data has become available both experimentally and through observations during actual earthquakes (5). Accordingly, high structural damping values may be used as an approximation to represent the response behavior of structures, while more rational methods are developed.

Energy absorption in the inelastic range is often handled through use of the so-called "ductility factor". The ductility factor is the ratio of the maximum useful (or design) displacement of a structure to the "effective" elastic limit displacement, the latter being determined not from the actual resistance-displacement curve but from an equivalent elasto-plastic function. Ductility levels for use in normal design range from as low as 1.0 to 1.3, or nearly elastic, to more than 5, when a great deal of energy can be absorbed in elastic deformation. Our ability to estimate such levels of ductility -- or more correctly the load-deformation (resistance) function -- is based on laboratory observations of samples of materials

and simple members and connections subjected to dynamic shake table loadings. These tests are extremely valuable in extending our knowledge.

One need not reflect long about current response spectrum design approaches to realize that the spectrum may well not provide all the information required (or desired) to carry forward rational nonlinear analyses. Quantification of real margins of safety requires knowledge of resistance as well as loading and response. New research is required to supplement efforts that are being carried forward to gain further insight into the basic parameters that play a controlling role in the margins of resistance of structural systems.

### 3.4 Observations

The earthquake engineering community has been extremely fortunate in the last several years, having recorded more data, both measured and observed than in the previous fifty years. This data has enabled engineers to develop a data base of information relative to the performance of systems, components and structures that are similar to these features in nuclear power plant application in high seismic environments. The response of the El Centro Steam Plant to the 1979 Imperial Valley earthquake is representative and worth noting because the facility is similar in design and types of equipment to older operating nuclear plants (6). The 4-unit steam plant was built in stages between the mid 40's and mid 60's and was designed for a static lateral load of 20% of the dead and live loads. It is estimated that the plant experienced strong ground motion with a PGA of over 0.5g, yet the facility safely shutdown with extremely minor damage.

A pilot program has recently been initiated by an industry group to study similar data, and extrapolate findings to nuclear power plant equipment in an effort to assess the capability of older facilities to survive seismic events. It is anticipated that this and similar information will be useful in helping engineers qualitatively assess margins of safety inherent within our seismic design and construction chain.

### 3.5 Response of Equipment

The subject of equipment response and design to insure functional operation during and after an earthquake is one of the most important problems facing seismic industrial design today. The subject is not a simple one if for no reason other than that there are so many different types of equipment to consider, ranging from piping, vessels (with internals), valves, and snubbers, to control cabinets (with their mechanical and electrical contents), batteries, lighting, cable trays, ducting, etc. Many of these items have received detailed attention in recent years in studies devoted to ascertaining the response and resistance properties of generic classes of items. Many recent theoretical studies (7), (8), (9), have suggested valuable approaches in this highly complex area but much remains to be done. Unfortunately the subject is highly complex and not easily handled theoretically. The results of experimental studies have provided valuable contributions as well, especially when the results were made publicly available.

## 4. Development of Criteria for Seismic Evaluation of Existing Nuclear Power Plant Facilities

Newmark and Hall have developed specific recommendations (10) for the evaluation of existing nuclear power plant facilities. These recommendations and associated criteria consider the implications of various levels of response and damage for older systems, components and structures in the context of overall plant safety. The following issues are addressed in detail:

1. Selection of the earthquake hazard;
2. Design seismic loadings;
3. Soil-structure interaction;
4. Damping and energy absorption;

5. Methods of dynamic analysis;
6. Review analysis and design procedures;
7. Special topics such as underground piping, tanks and vaults, equipment qualification, etc.

Limitations of space make it impossible to summarize all of these issues.

## 5. Conclusion

In designing a new structural/mechanical system or reevaluating an existing system, one must take into consideration a plethora of criteria all of which can lead to different modes of stressing or straining at various locations. The design task is to optimize the situation to a degree to obtain a functional yet economical structure. The reevaluation task is to understand the expected behavior and determine, what if any retrofits are required to gain an acceptable response. This must all be done in consideration of various inherent design concepts which are often different in existing facilities. The procedure of arriving at or modifying a design is not straightforward and really is an art, especially when it is realized that the structure may be subjected to a combination of extreme loadings somewhat different than that envisioned during design. Obviously then, the designer must have a good understanding of structural behavior and must be able to not only envision all likely loadings, but the system response under various combinations. A system so designed will stand the test of time and new information which will give us even added insight into realistic structural/mechanical behavior. The lack of ability to envision such behavior, or alternatively the reliance on standard code procedures alone along with automatic analytical analysis without the insight noted, is precisely what has led to some of the catastrophic failures of recent years as well as the costly retrofits that have had to be made in many instances.

These considerations gain heightened importance when reevaluating the capability of existing facilities. There often are difficult economic and physical constraints (e.g. radioactive environment, lack of space, etc.) for which engineers must contend in addition to the more usual challenges. The criteria referenced in section 4 will be useful to future reevaluation efforts; however, it must be emphasized that such investigations be undertaken with care and optimally under the direction of an experienced board of experts.

The reevaluation efforts should be well documented to demonstrate that what has been accomplished is reasonable, is adequate in the light of the agreed upon criteria, meets acceptable margins of safety (very hard to document in most cases), and in all respects leads to the desired performance in a cost-effective manner. This goal is rather easy to discuss generally, but very difficult to execute. In the end there is no substitute for engineering judgment.

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