SEISMIC REVIEW OF EXISTING NUCLEAR POWER PLANTS

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SUMMARY

Because of developments in the fields of earthquake and structural engineering over the last two decades, the codes, standards and design criteria for Nuclear Power Plants and other critical structures have changed substantially. As a result, plants designed only a few years ago do not satisfy the requirements for new plants. Accordingly, the Regulatory Agencies are requiring owners of older Nuclear Power Plants to re-qualify the plants seismically, using codes, standards, analytical techniques and knowledge developed in recent years.

Seismic review consists of three major phases: (1) Establishing the design and performance criteria, (2) Re-qualifying the structures, and (3) Re-qualifying the equipment.

The design criteria and the levels of earthquake excitation are dependent on the presence of soil-structure interaction, particularly for soft soil sites and embedded structures. The original design spectra may be significantly altered in such cases. Structural design codes, and particularly mechanical and pressure vessel codes have changed significantly in recent years and present some difficult problems for re-qualification and design.

Structural re-qualification consists primarily of analytical studies of the existing structures. Several factors aid the analysis—the configurations are fixed, tests can be easily performed to obtain more accurate material properties, and forced vibration testing can be performed to establish dynamic properties.

Equipment and piping systems re-qualification involves analysis and extensive in-situ, forced vibration test programs. A combination of the methods appears to be most desirable, particularly for structurally complex or rigid equipment.

Some of the difficulties encountered in the seismic review are the verification of as-built structural and equipment configurations, the extent of non-linear effects such as cracking of concrete members, selection of performance criteria for electrical equipment, lack of access because of high radiation exposures.

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1. Introduction

1.1 The Problem

Currently, at least three United States nuclear plants are undergoing detailed seismic review of their safety related structures, systems, and components. The scope of the requalifications ranges from complete reanalyses of the facilities to the seismic requalification of the most critical systems, such as the nuclear steam supply system. These efforts have been undertaken on the request of the U.S. Nuclear Regulatory Commission (NRC), formerly the U.S. Atomic Energy Commission, or have been initiated by utilities that own older plants in higher seismic areas.

The authors of this paper have been recently involved in the seismic review of existing nuclear power plants in the United States; this paper is a brief summary of their experiences. Detailed results of their analyses and tests will be published in later, separate papers.

1.2 Why Requalification?

The designs of the oldest plants were based on the application of static lateral loads on the structures and equipment, whereas modern analyses use sophisticated analytical techniques aided by the rapid development of computer technology. Furthermore, since the first commercial plants were designed and constructed, the various design codes (civil, mechanical, electrical, etc.) have changed significantly, particularly as applied to nuclear facilities. New plants located near older units have prompted new geologic and seismologic discoveries that affect the site design parameters for the existing units, and it is difficult to justify designing two adjacent units according to very different seismic criteria. Accelerograph records from the San Fernando earthquake of February 9, 1971, revised upward the commonly accepted horizontal and vertical peak ground accelerations. The 200 or more records provided by this earthquake also aided the development of more refined and wider response spectra [1,2]. These new spectra are considerably more conservative than some of the spectra used for older plants [3]. Finally, the regulatory agencies and utilities have made continuous efforts to modernize and update the plants, particularly in the areas of safety. Seismic reanalysis and redesign have been required for many systems that have been improved or modified. The installation or modification of systems for protection against pipe breaks outside the primary containments, impact and jet impingement loads, off-gas modifications, and new safety systems are prime examples. These systems and components must be designed under seismic design criteria commensurate with current design criteria.

1.3 Some Design Requirements and Code Changes

The most important criteria changes have been the increased peak ground accelerations and the wider response spectra with higher response amplifications. New analyses are required, which account for possible design spectra modifications due to the presence of soil-structure interaction (SSI). In addition, the spectra may also be modified by the presence of soil amplifications and the spatial relationship between the causative fault and the geology of the site. Liquefaction studies are now required to determine the potential for soil failures at the site. It is no longer possible to use a single time-history of an existing earthquake record, such as the El Centro record of 1940, for design. Instead, more representative, artificially generated time-histories and closely matching design response spectra must be used. Whereas previous seismic analyses were conducted for three independent directions, now the effects of all three components must be considered simultaneously. Because modern plants must be protected against multiple hazards occurring simultaneously, the seismic stresses must be combined with other stresses caused by various loading conditions such as pipe breaks, pressurization due to pipe breaks, or operating load transients on the equipment. The allowable damping values for structures and equipment have also changed, and the new codes have revised allowable stress values. Increased analytical accuracy, particularly because of the wide use of the finite element method, permits much better understanding of such common problems as stress concentrations around openings and other discontinuities. In some cases, these more advanced analytical methods have revealed weaknesses in the simple assumptions used for the design of older facilities.

Other design code changes include increased requirements for lap lengths and bond lengths for reinforcing steel in concrete and the introduction of usage factors, thermal cycles, pipe whip, and differential anchor movements for piping and mechanical equipment. These requirements are vastly different from the design requirements for plants built in the early 1960s [4]. The qualification of electrical equipment and electrical components has also been affected by new vibration test requirements [5].

2. The Requalification Process

The requalification process of an existing plant is similar to the design process for a new plant, except all structural and equipment systems are already designed and built and the time schedule is much shorter. The design effort for a new plant takes several years, while a seismic review usually takes about a year, depending on the scope of the effort.

Seismic review and requalification consist of the following major tasks: (1) establishing the design and performance criteria; (2) conducting a thorough geologic and seismic survey of the area and establishing the peak design accelerations for the Operating Basis Earthquake (OBE) and the Safe Shutdown Earthquake (SSE); (3) conducting a soils investigation; (4) requalifying the structures; (5) requalifying the equipment and piping systems; and (6) preparing a final report.

3. Design and Performance Criteria

The design and performance criteria for the requalified plant are similar to those for new plants. The latest codes, criteria, and the most advanced analytical techniques should be used because deviations from current requirements need to be justified so that safety is not compromised. Not all requirements of new codes need be followed, particularly if safety will not be compromised by relying on ductility or nonlinear response.

4. Geologic and Seismologic Survey

This survey may already have been performed if new units are planned for the same site. If not, a full geologic investigation must be conducted to locate any potentially active faults near the site. The site seismicity survey is necessary for establishing the expected peak accelerations for the OBE and the SSE. Again, the most advanced techniques and instrumentation are used to establish these site parameters.

5. Soils Investigation

The potential for soil instability at the site must be evaluated. Generally, these studies consist of the following major items [6]: (1) A comprehensive field investigation to obtain additional information on the subsurface soil conditions at the plant site and to obtain samples of the in-situ soils for laboratory testing. (2) A comprehensive laboratory testing program to classify the soils and to evaluate their dynamic characteristics. This may include resonant column tests and strain-controlled cyclic triaxial tests to evaluate the dynamic properties of the major soil types present, and stress-controlled cyclic triaxial tests on sandy materials to evaluate their liquefaction characteristics under simulated earthquake loading conditions. (3) Interpretation of the test results, especially the liquefaction tests, to determine a meaningful correlation of the laboratory behavior and the field behavior of the soil deposit under seismic excitation. (4) Evaluation of the liquefaction potential at the plant site based on a comparison of the cyclic shear stresses required to cause significant strains in laboratory samples with the equivalent uniform cyclic shear stresses induced in the soil by the SSE. This evaluation must also determine the safety factors and the possibilities for permanent movements or ground failures. (5) Evaluation of the potential for ground instability under higher accelerations.

6. Soil-Structure Interaction Analysis

The SSI analysis will determine design ground motions (in the form of acceleration time-histories and response spectra) to be used in the analysis of the structures and the supported equipment at sites with foundation materials other than rock. Such an analysis is an important step in the requalification study because it can reveal ground motion characteristics that differ significantly from those considered in the original design. The analysis may indicate that the original design spectra of the ground motions were too conservative or too unconservative for the existing soil conditions or that the shape of the specified response spectra is too wide for the site conditions, particularly in the mid-range structural frequencies of 3 Hz to 10 Hz.

The usual current procedure for determining design ground motions assumes that the free field (a point at the site away from the influence of the structures) has response spectra as defined in Regulatory Guide 1.60 [1]. These are design spectra based on a statistical envelope of spectra recorded at several sites [2], and represent an envelope of spectra for use at most sites. The SSI study is meant to determine a more appropriate range of response spectra for the particular site, which accounts for the influence of the site soil conditions and the dynamic properties of the various structures on the site.

If the plant was originally designed without a comprehensive dynamic analysis, the structures are not likely to be amenable to simple dynamic analysis. The structures may be truly three-dimensional in their behavior and exhibit dynamic characteristics -- in particular, strong torsional response -- that are not generally found in newer plants. Determining the influence of these characteristics is one of the goals of the SSI analysis.

6.1 Methods of Analysis

A number of techniques are currently available for SSI analyses, but in this rapidly developing field of research, no generally accepted technique is yet available.

Current methods of analysis consist of two broad categories: lumped parameter methods and finite element methods. With lumped parameter methods, the elastic and inertial properties of both the soil and the structures are combined in a simple model. The structures are typically represented as a system of lumped masses connected by a series of beam or spring elements. The soil is modeled as a series of springs and damper elements that are attached to the structural model. While this model is easy to analyze, determining the correct structural and soil properties can be complex, and considerable judgment and experience are needed to produce meaningful results. This method is most appropriate for surface structures with relatively simple dynamic characteristics.

For more complex systems, the finite element approach is more appropriate, although it is considerably more time-consuming and expensive. The analysis can be one-, two-, or three-dimensional. At present, most available computer programs consider either one- or two-dimensional models because three-dimensional analyses are still prohibitively expensive. In a two-dimensional analysis, the soil and the structures are modeled as assemblages of two-dimensional linear or nonlinear finite elements. Because the finite element approach is widely used, the rest of this discussion on SSI is limited to this approach.

6.2 Analysis Procedure

A finite element analysis generally contains the following steps: (1) Specification of the design motion at some point in the free field by means of the peak acceleration and the appropriate design response spectra. (2) Generation of artificial acceleration histories with spectra that match closely the selected free field spectra. (3) Modeling of the earthquake motion in the soil by the vertical propagation of shear and compression waves from the underlying bedrock [7]. One-dimensional wave propagation techniques are used to deconvolve the input motion to obtain the horizontal and vertical components of motion at a depth corresponding to the selected base of the SSI finite element model. (4) Computing the response at points of interest by applying the deconvolved motions at the base of the finite element model. Points in the model that are at the same level as the original free field motion and sufficiently removed from the structure should have similar computed accelerations and response spectra to those of the free field motion. At points on this level and adjacent to the structures, the motion and spectra will vary from the corresponding free field values as a result of SSI. (5) Study of the resulting motions and their response spectra, with manual modification using sound engineering judgment, before any motions or spectra are adopted for use in subsequent analyses of structures and equipment. Because of limitations of the method and the reliability of the soil and structure properties used, the analysis is best used to indicate response trends rather than to provide reliable, detailed numerical results.

6.3 Development of the Models

Development of a complete two-dimensional finite element SSI model requires the cooperation of structural and soils engineers. Any modeling decisions that affect either discipline should be considered carefully.

The first step of the modeling process is to determine along which vertical planes the SSI effects will be considered. This decision depends primarily on the layout of plant structures. The lines should pass through those portions of the structures expected to contribute most significantly to interaction. Once the planes for the analyses have been determined, the finite element models for the soil can be constructed on the basis of the soil profile and the soil properties (density, shear modulus, Poisson's ratio, damping, nonlinear characteristics, etc.). Nodal point locations and element sizes should be selected so that critical points on the structures correspond to mesh points on the models.

The structural models are then constructed. As noted, older plants may exhibit three-dimensional dynamic behavior, while the SSI models of the structures are two-dimensional. The current procedure for constructing these models involves two steps: (1) constructing three-dimensional, fixed base models of the structures and extracting mode shapes and frequencies for them, and (2) constructing, by trial and error or other methods, equivalent two-dimensional finite models that will be used in the SSI model. The three-dimensional structural models may be lumped mass or finite element models. Ideally, these are the same models to be used later for the detailed structural analyses. The required two-dimensional mode shape components in the plane under consideration are extracted by separating the components of the mode shapes in that plane, or by a dynamic condensation procedure that automatically reduces the three-dimensional model to two dimensions. The two-dimensional model must have the same characteristics in the plane of interest as the original three-dimensional model.

Special problems may arise when the structural model is developed. Multiple structures resting on a single base mat are common in older structures. Each structure can be modeled independently and connected at a set of common node points at the foundation level, while the elements overlap in the plane of interest. Because two-dimensional (plane strain) analysis assumes that the model is a strip of uniform width, the effective width of each overlapping building must be estimated. Finally, if structural modifications are considered, the dynamic characteristics of the structures may be affected and this influence on the SSI study should be considered. Fortunately, minor changes in the dynamic properties of the structures do not significantly affect the SSI unless the structures are near resonance with the soil [8]. Thus, it is important to minimize the detailed structural analyses and modeling techniques for this phase of requalification.

7. Structural Requalification

Nuclear power plant structures in the United States are classified into two seismic categories [9]: Category I, which includes all structures necessary for the safe shutdown and subsequent safety of the plant and the environment; and Category II, which includes all structures not necessary for the safe shutdown and subsequent safety of the plant. For economic reasons, structures subject to seismic requalification include only Category I structures, structures attached to Category I structures, and structures whose collapse will affect Category I structures. However, both Category I and II structures must be included in the SSI analyses if their response might influence the results of the analyses.

Structural requalification consists primarily of analytical studies of the structures. This may be combined with low-amplitude vibration testing. As noted, the structures must be modeled with minimal detail for the SSI analysis. For the structural requalification, the full models are used, with substructure analysis remaining a viable alternative for locally complex structures. If the structural models for the SSI are analyzed for stress, the analysis can be used as a first pass to determine if any structures are overstressed. If problems are revealed, detailed analysis is used to verify them. Preliminary structural modifications then begin, but final design should wait until the SSI studies are completed and the final response spectra at the building foundations are established. Thus, at a relatively early stage of the entire requalification effort, the possible final costs for upgrading the plant structures to the new seismic criteria can be estimated. After SSI analyses are completed, the final models of the structures are analyzed, together with the required modifications. Then, floor response spectra in the structures are generated for use in the requalification effort of the equipment and piping systems. The initial effort on the equipment and piping should proceed at the same time as structural requalification work.

In contrast to the structural analysis of new plants during their design stage, structural requalification analysts work with existing structures and known systems configurations. Of course, the analysts must familiarize themselves thoroughly with the plant, first through existing drawings and then through regular visits to the plant.

If structural deficiencies are noted in the detailed models, it may be advisable to test the actual strength of core samples of the existing structural materials, particularly concrete. With time, concrete increases in strength significantly beyond the design values [10]. This is one possibility for minimizing the conservatism built into the codes.

7.1 Some Difficulties

Requalification of an existing plant may present difficulties that are not usually encountered in the design of a new plant. Unless the plant's design and construction included an extensive quality assurance program, some structural drawings, particularly as-built drawings, will be unavailable, out of date, or inconsistently revised. Collecting all necessary drawings is a slow, time-consuming process. Structural modifications would present additional difficulties. It may be difficult to add structural elements around existing equipment or piping, particularly because a significant amount of unused space is rare. Because modifications would be designed according to the latest codes, some design discrepancies would be unavoidable because different codes would have been used for different portions of the structure.

7.2 Vibration Testing of the Structures

Vibration testing of the structures at low acceleration levels can significantly aid in analysis and requalification of the structures. The testing should be conducted while the plant is not operating (for example, while it is refueling).

All types of structures can be tested, from light steel structures to massive reinforced concrete structures [11,12]. The results are used to verify the results from the analyses, particularly the mode shapes and the natural frequencies. If the analytical results differ from those generated by the vibration testing, the differences must be justified. Typically, differences will be caused by analysis simplifications, incorrect assumptions in material properties, nonlinearities in the behavior of the structure that cannot be reflected in linear analyses, SSI at low amplitude levels, etc. The testing can be used to verify the accuracy of the analysis, but the analysis will still control the distribution of forces and stresses for the desired acceleration levels. Testing can also give valuable data on damping that can be used in the later analysis. Note that the damping values recommended by Regulatory Guide 1.61 [13] may be conservative because higher values will often be indicated by the tests [14].

Structures excited at two or more levels of acceleration may reveal nonlinearities in the range tested. The nonlinearities for some structures, such as concrete stacks, may lead to significantly lower frequencies and increased damping values. In the case of flexible structures, this may be very advantagous, as lower frequencies, especially below 2 Hz, lead to much lower spectral values and thus accelerations.

Vibration testing may also reveal potential structural problems. For example, local resonances in light steel floors may appear during a test of a massive concrete structure, thus indicating that stiffening is desirable in the area of greatly amplified response.

8. Equipment Requalification

The equipment of a nuclear power plant consists of mechanical and electrical components: mechanical equipment consists of pressure vessels, pumps, generators, turbines, heat exchangers, condensers, tanks, fans, piping, valves, etc.; electrical equipment consists of supporting structures (cabinets and other structural supports) and electrical components (switches, relays, gages, indicators, etc.). For seismic requalification, equipment is generally divided into Categories I and II on the same basis as structures. Again, for economic reasons, only Category I equipment is subjected to the detailed requalification process, while Category II equipment can be evaluated either by simplified analyses or a site inspection.

In the early plants, piping systems and mechanical equipment were not subjected to detailed seismic analysis because today's analytical tools were not available. Forces originating from pipe breaks were also not evaluated. Consequently, the loads to be resisted by a particular piece of equipment (especially one with attached piping) can be an order of magnitude higher than the loads used in the initial design. The higher loads often require structural modifications to ensure the safety of the particular piece of equipment.

As-built equipment drawings and design and operating criteria are again difficult to obtain, particularly for an older plant. Furthermore, when an equipment modification is necessary, modification will be limited by space and operational requirements, strength of the structures to which the modification may be attached, and the stress release required when a weld is made to a pressure vessel or similar equipment.

Over the last five years, shake table tests and forced vibration tests have become quite common and useful in the design and analysis of equipment and structures. The shake table test is now often used for the seismic qualification of mechanical and electrical equipment [15] and is generally used as a proof or a qualification test, using one of several methods: sine sweep tests, sine beat tests, or random input motion tests [5].

Forced vibration tests are useful for verifying or modifying analytical models, as previously noted. These tests can usually be performed at low-amplitude levels; however, for equipment that can be isolated, the forced vibration test may be used as a proof or a qualification test. A variation of the forced vibration test is the snap back test, performed by initially displacing the structure or piece of equipment and releasing it to vibrate freely. The major advantage of these tests is that the dynamic characteristics of the as-built condition are obtained.

Several methods are available for seismic requalification of equipment in an existing plant.

8.1 Comparison with Similar Seismically Qualified Equipment

Over the last 15 years, construction and design have remained substantially unchanged for some equipment, including valves, motors, and some electrical equipment. Because equipment in older plants is often similar to equipment that has been qualified for today's code requirements, comparison with such qualified equipment, noting any design changes or modifications, allows simple and inexpensive qualification.

8.2 In-Situ Proof Testing

The in-situ proof test can be performed only if the particular piece of equipment is not essential for the shutdown condition of the existing plant. It is generally performed by forced vibration tests, and therefore the available size and type of shakers limit the equipment that can be tested.

8.3 Combined Testing and Analysis

This is probably the most powerful method available for requalifying equipment. The equipment is subjected to a forced vibration test to determine its frequencies, damping values, and mode shapes. If two or more forcing levels are used in the forced vibration test, nonlinearities in that range would become apparent by change in the natural frequencies and damping values. However, nonlinearities outside this range (at larger amplitudes) would be difficult to predict. With the test results available, analytical models can be modified or verified to account for as-built conditions. Confidence in the extrapolated results for higher force levels is enhanced if the analytical model reflects the actual properties of the as-built conditions [16].

8.4 Shake Table Tests

The shake table test has the following limitations. Equipment to be tested must be within the size and weight limits of the shake table used. Although sometimes a spare piece of equipment can be used, equipment in older plants may be out of production, thus requiring the item to be disengaged from its position in the plant. (Purchasing a seismically qualified replacement is often less expensive than testing the actual item.) Furthermore, unless a portable shake table is available, equipment to be tested must be transported to the testing facility.

8.5 Theoretical Analysis

In some cases, such as in high-radiation zones, none of these methods for requalifying equipment can be used. Instead, a detailed seismic analysis must be performed even though it may be more difficult to estimate the effects of appendages, piping, and the boundary conditions.

9. Conclusions

The seismic review of an existing nuclear plant consists of three major phases: (1) establishing the design and performance criteria, (2) requalifying the structures, and (3) requalifying the equipment. Although these phases resemble those of a new facility, they take less time -- perhaps one year rather than several years. Thus, requalification requires intensive effort; close cooperation from the different disciplines represented; close cooperation among the project personnel, the client, and the power plant personnel of the client; and the availability of a large enough, qualified staff for the necessary seismic analyses and tests.

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