SUBSYSTEM RESPONSE DETERMINATION FOR THE US NRC SEISMIC SAFETY MARGINS RESEARCH PROGRAM

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SUMMARY

In order to evaluate the conservatisms in the seismic design of nuclear power plants, the hazards due to seismically induced accidents are to be determined from a probabilistic system model of a nuclear power plant. This Seismic Safety Margins Research Program (SSMRP) is sponsored by the US Nuclear Regulatory Commission and managed by Lawrence Livermore Laboratory. The program has been organized into several phases; the initial phase is to be completed by May 1980. This organization is essentially recognizing that the seismic analysis and design of nuclear power plants is a complex interdisciplinary task with enormous demands placed on the limited available research funds. One of the results of Phase I of the SSMRP will be an overall system model composed of a series of functions representing the various stages in the seismic analysis and design process, i.e., seismic input, soil structure interaction, major structural response, structural subsystem response, fragility of structures and components, and the event/fault tree chain leading to core melt. Each function defines a "best estimate" value and its variation with respect to differing physical parameters. In addition, an assessment of the accuracy of the mathematical models to represent the physical phenomenon is made. Exercising the overall systems model leads to an estimate of the probability of release of radioactive material as a function of earthquake size. The actual value of the probability of release of radioactive material computed in the SSMRP Phase I has little validity in an absolute sense due to the incompleteness of the model and the lack of pertinent data, particularly, in the area of fragility of structures and components, and its anticipated wide variations. However, the probability of release and its variation with varying physical and modeling parameters is of value in assessing the relative importance of the various links in the seismic analysis methodology chain through calculations of their contribution to uncertainty in the result. These results will help direct the allocation of research funds in future phases of the SSMRP. This methodology developed for Phase I of the SSMRP will be exercised on the Zion Nuclear Power Plant, Zion, Illinois, USA.

A report on the progress of the structural subsystem response project is to be presented. For the SSMRP, the term subsystem denotes those components and systems whose behavior during a seismic event may be determined decoupled from the major structural response. Typically, the mathematical model utilized for the major structural response will include only the mass effects of the subsystem and produce the support motions to be applied for subsystem seismic qualification. The goal of this project is to develop transfer functions to be used in the overall systems model. These transfer functions will relate the subsystem response to the input environment; i.e., the subsystem support motion. The "best estimate" methodology will be utilized to develop transfer functions for the overall systems model. These transfer functions will be dependent on a number of parameters such as physical properties of the subsystem.

The initial portion of this task deals with a definition of the state-of-the-art of seismic qualification methods for subsystems. To facilitate treatment of this broad class of subsystems, three classifications have been identified; multiply supported subsystems (e.g., piping systems); mechanical components (e.g., valves, pumps, control rod drives, hydraulic systems, etc.); and electrical components (e.g., electrical control panels). Descriptions of the available analysis and/or testing techniques for the above classifications are sought. The results of this assessment will be applied to the development of structural subsystem transfer functions.

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1. Introduction

In order to estimate the conservatisms in the current United States Nuclear Regulatory Commission's (US NRC) seismic safety requirements and to develop improved requirements, the Seismic Safety Margins Research Program (SSMRP) [1] has been initiated and sponsored by the US NRC, and managed by the University of California's Lawrence Livermore Laboratory (LLL). The SSMRP is composed of three phases. The initial phase centers on the development of a probabilistic methodology that more realistically estimates the behavior of nuclear power plant structures and systems during a hypothesized earthquake. This methodology will be used to perform sensitivity studies to gain engineering insights into seismic safety requirements. The resulting methodology of the initial phase of the program will yield estimates of the probability of failure of structures, systems, and components and the probability of radioactive releases over a range of earthquake levels. The value of these estimates and their anticipated wide variations lies in their use to help determine research priorities for the SSMRP Phase II. Tracking the source of these variations as a function of the essential components of the seismic analysis methodology will be of principal importance. The allocation of future research funds will be partially based on the anticipated reductions in the aforementioned variations of the probability of failure of structures, systems, and components and the probability of radioactive releases due to the results of the research. Candidate areas for additional research include but are not limited to experimental investigation of dynamic behavior and failure of systems, analytical development, and data collection. Throughout the SSMRP, the methodology will be tested against experimental data whenever possible. The second phase of the SSMRP will utilize the methodology of Phase I to estimate the conservatisms in the current US NRC seismic safety requirements. In addition, research will be performed in those areas identified during Phase I as being most beneficial. Finally, this improved methodology will be used to refine estimates of the conservatisms and to define the seismic contribution to reactor risk. The third phase of the SSMRP will utilize the improved methodology of Phase II as a basis for recommending changes in the US NRC seismic safety requirements by developing a balanced deterministic seismic design methodology.

The analysis and design of a nuclear power plant to resist earthquake hazards requires a significant multi-disciplinary effort [2]. This effort includes contributions from geologists, seismologists, and engineers specializing in soils, and structural, mechanical, and electrical design. There is a strong motivation to examine the process of seismic analysis and design of nuclear power plants in an overall system context. This is principally due to the widely held belief by the nuclear industry and the US NRC that a compounding of conservatisms occurs in the current process. That is, at each stage of the present analysis and design process, conservatisms are introduced to account for uncertainties. However, minimal emphasis is placed on the compounding of these conservatisms due to their introduction at previous and subsequent stages of the design. The result may be an over-conservative design with respect to the seismic hazard in comparison with (and perhaps at the expense of) other hypothesized accident conditions and normal operating conditions. The methodology to examine the seismic analysis and design of nuclear power plants in an overall system context is being developed in the SSMRP Phase I.

A general description of the systems analysis approach to be utilized in the SSMRP Phase I begins with an overview of the various stages in the seismic analysis and design process. Detailed descriptions of this process are available in the literature [2] and will not be duplicated herein. However, a brief description of each link in the seismic analysis and design methodology chain and its role in the SSMRP Phase I is presented. Figure 1 depicts the seismic analysis and design methodology chain. The seismic input phase [3] concentrates on defining the earthquake hazard at the nuclear power station site. This includes an estimate of the seismic hazard function, i.e., the relationship between the probability of occurrence and a measure of the size of the earthquake, and a description of the free-field ground motion. Examples of possible forms of the free-field motion are time histories, response spectra, Fourier amplitude spectra, power spectral density functions, peak values of acceleration, velocity and/or displacement, etc. The spatial and temporal variations of the ground motion at the site will also be investigated. The soil structure interaction link in the chain has the broad objective of transforming the free-field ground motion at the site into base-mat or in-structure response accounting for the interaction of the soil with the massive stiff structures typically present at a nuclear power station. Those aspects of the soil structure interaction phenomenon which have a significant effect on the dynamic behavior of the overall system will be accounted for in the analysis. Hence, an evaluation will be made of the significance of items such as structure to structure interaction, and nonlinear behavior of the soil. The output of the soil structure interaction phase of the process is the base-mat response and, in some instances, the in-structure response to be utilized in subsequent stages of the analysis. Determination of the major structural response [4] follows the soil structure interaction phase. The term "major structures" most commonly denotes buildings; however, for the SSMRP, major structures include all structures, components, and systems whose dynamic characteristics affect the overall behavior of the nuclear power station during an earthquake. For example, large components such as the reactor pressure vessel, and heat exchangers are included in the category of major structures. The major structural response link of the chain concentrates on determining the structures' dynamic response for two main purposes. First, the ability of the structure to perform its design function during and after the earthquake must be assessed. For buildings, this includes providing support for systems contained therein. For vessels, this includes providing a leaktight pressure boundary. Second, the major structures act as transmitters of vibratory motion to the support systems of emergency and power generation equipment for subsequent evaluation. The final link in the traditional seismic analysis and design methodology chain utilizes the output from the major structural response to investigate the dynamic response of subsystems [5]. The term "subsystem", as used in the SSMRP, denotes those components and systems whose behavior during a seismic event may be decoupled from the major structural response. Typically, only the mass of subsystems is incorporated into the mathematical model used in the overall dynamic response determination. Examples of typical subsystems are: mechanical components such as pumps, valves, and motors; electrical components such as control systems, and cables and piping systems. The above four areas comprise the seismic analysis and design methodology chain. However, to perform the system analysis, several additional ingredients are required and discussed below.

The systems analysis portion [6] of the SSMRP encompasses two aspects. The first is to examine and develop systematic representations of the nuclear power station's reactor systems.

This will most likely be achieved using event tree/fault tree methodology. Two types of reactor systems will be considered: systems whose failure will cause the initiation of an accident sequence leading to core melt; and systems designed to mitigate the consequences of such an accident. Phase I of the SSMRP will investigate only accident sequences which lead to a core melt. It is clear the development of the event trees and fault trees will dictate the systems and structures for which dynamic response will be determined, i.e., the event trees and fault trees are the initiating point for the model. The second aspect of the systems analysis task is the development of an overall computational approach which computes the probability of failure of structures, components, and systems and the probability of radioactive releases and variations in these probabilities due to uncertainties in the seismic analysis and design methodology chain. Figure 1 schematically depicts this procedure. In addition, the nature of this study and the resulting figures of merit require a detailed examination of the fragility of structures, components, and systems due to seismic loading conditions [7]. This extremely difficult task plays a key role in the SSMRP.

The systems model for the SSMRP emphasizes realism in contrast to the conservatism emphasized in design. Thus, a "best estimate" representation of each link in the seismic analysis and design methodology chain must be established. Also, variations about this "best estimate" must be considered. These variations result from uncertainties in the physical characteristics of the system and phenomenon and the ability (or inability) to accurately predict system behavior by analytical means. Defining, classifying, and quantifying uncertainties is difficult at best and currently only a preliminary indication can be provided. Two broad classifications of uncertainties have been identified: random and systematic. Uncertainties inherent in the physical and phenomenological aspects of the problem are called random; whereas, uncertainties associated with the ability to model these aspects are called systematic. It is the latter type of uncertainty which may lend itself to reduction by research. An attempt to establish the state-of-the-art in each of the seismic analysis links of the methodology chain plays a key role in defining the "best estimate" representation and in establishing base-line data for future phases of the SSMRP. In addition, the requirements of the SSMRP systems model place unique demands on each aspect of the program. The overall objective of the SSMRP is to examine probabilities of failure which necessitates considering a wide range of excitation levels. The specification of an Operating Basis Earthquake (OBE) and a Safe Shutdown Earthquake (SSE) have significance only in terms of defining design levels for structures, components, and systems. It is anticipated that the model will be exercised for excitation levels varying from low levels to multiples of the SSE level. This requires innovative thinking as to the "best estimate" representation of each aspect of the phenomenon.

The following text describes the proposed method of approach for the subsystem response phase of the SSMRP. A progress report will be presented to supplement this description.

2. Zion Nuclear Power Plant

The methodology of the SSMRP Phase I will be demonstrated on an existing nuclear power station -- the Zion nuclear power plant unit 1. The Zion plant is located on Lake Michigan about 1.5 miles (2.3 km) east of Zion, Illinois, USA and about 40 miles (62.5 km) north of Chicago, Illinois, USA. The plant was designed by Sargent and Lundy Engineers for Commonwealth Edison, the owner and builder. The plant consists of two NSSS units with a power rating of 1100 MW(e) each.

3. Subsystem Response Determination

3.1 General

The term "subsystem" as used in the SSMRP denotes those components and systems whose behavior during a seismic event may be decoupled from the major structural response. Normally only the mass of subsystems is accounted for in the overall dynamic analysis of the nuclear power station. Examples of typical subsystems are: mechanical components such as pumps, valves, and motors; electrical components such as control systems and cables; and piping systems. The broad objective of the subsystem response project of the SSMRP is to develop transfer functions which relate subsystem dynamic response to the input environment, e.g., the subsystem support motion. In keeping with the overall goal of the SSMRP, a "best estimate" model of the dynamic response phenomenon must be determined. In conjunction with this "best estimate" model, possible sources of uncertainties and their effect on the subsystem response transfer functions must be identified and quantified. The following sections describe the current plans to achieve this goal.

The subsystem response project must work in close coordination with the systems analysis project [6] and the fragility project [7]. Development of the event trees and fault trees is the sole motivation for which systems, and portions of systems, dynamic response parameters must be determined. A preliminary list of systems to be considered for the Zion nuclear power plant is shown in Table I. The reactor coolant system is of interest for two main purposes. First, the event tree development is based on the premise of a series of accident conditions. At this time five such accident conditions or initiating events have been hypothesized for the SSMRP: reactor pressure vessel rupture; three LOCA conditions corresponding to equivalent primary coolant pipe break sizes of greater than 6 in. (15.2 cm) diameter, 2-6 in. (5.1-15.2 cm) diameter, and less than 2 in. (5.1 cm) diameter; and a transient. The subsystem response and the major structural response projects along with the fragility project must provide the methodology to establish the probability of occurrence of an initiating event for a given seismic event. Second, those portions of the reactor coolant system which function coincidentally in an engineered safety system require consideration. The remaining systems encompass those necessary to mitigate hypothesized accident conditions.

Coordination between the subsystem response project and the fragility project must be quite close during development of the overall systems model. The dynamic response parameter(s) for a given subsystem must be related to its fragility to provide the necessary input to the systems model. This task is difficult if one considered only a single component excited to its design level, and it could become overwhelming in the context of the systems model where 600-1000 components or piping runs may require consideration at excitations varying from low to very high levels. It is clear that a balance of effort between computational feasibility and "best estimate" response will need to be achieved. Differences in the two will be treated as uncertainties in the response methodology.

3.2 State-of-the-Art Review

A basic task in the subsystem response project is to define the state-of-the-art of response determination and seismic qualification of subsystems for a nuclear power plant. Typically, subsystem response is estimated using analytical methods, testing methods, or a combination of the two. The state-of-the-art review will assess the advantages and disadvantages of existing methods and methods under development. This assessment will emphasize a realistic or "best estimate" prediction of subsystem response in conformance with the philosophy of the systems model. An attempt will be made to assess the accuracy of each technique and factor this variation into the systems model. In conjunction with this "best estimate" response, an evaluation of important variables and their resulting influence on response will be made. The evaluation will concentrate on parameters associated with the subsystems themselves rather than the input environment which is more properly treated in the major structural response and soil structure interaction areas. It is anticipated that for Phase I of the SSMRP, sources of random uncertainties such as variations in material properties and support conditions will be transferred into variations in the eigensystem (including damping) for the subsystem. Sources of systematic uncertainties reflect the inability of analytical functions to adequately represent subsystem response. For SSMRP Phase I, this will include the effect of nonlinear behavior of subsystems, e.g., subsystems whose behavior is inherently nonlinear (core structures, etc.) and subsystems whose behavior is approximately linear at low levels of excitation but most certainly will behave nonlinearly at elevated excitation levels and in approaching failure.

The assessment of response determination methods will be coordinated with a categorization of subsystems according to similarity of dynamic behavior. A treatment of categories of subsystems will be a useful tool for the systems model due to the potentially large number of subsystems to be considered. An initial attempt of classifying subsystems identified mechanical components, electrical components, and multiply supported subsystems as three distinct groups. Further sub-classifications have been proposed and alternatives recognizing the sizes of subsystems, criticality, functionality, fragility parameters, and nonseismic loading conditions. Classifications which provide the greatest benefit to the systems model will be selected.

To accomplish this state-of-the-art review, it is the intent of the SSMRP to obtain broad participation from the most knowledgeable portion of the technical community.

3.3 Subsystem Response Analysis

Phase I of the SSMRP will, strictly speaking, consider the seismic response phenomenon to be linear. The effect of nonlinear behavior will be approximated by the introduction of systematic uncertainty into the "best estimate" characterization of the transfer functions. Current plans are to examine a portion of a system in detail including the effects of nonlinear behavior during the excitation and compare the resulting response with a linear approximation. The comparison will be made for a range of excitation levels applicable to the overall systems model. The results will provide some indication as to the type of systematic uncertainty to be introduced into the systems model.

4. Summary

A general description of the SSMRP Phase I has been presented to demonstrate the relationship of the Subsystem Response Project to the overall program objectives. A rather detailed description of the planned activities of the project were provided. A report on the progress of these tasks will comprise the oral presentation.

5. References

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TABLE I
CRITICAL SYSTEMS IDENTIFIED IN A PRELIMINARY REVIEW OF ZION I

Reactor Coolant System
Containment Fan Cooler System
Containment Spray System
Auxiliary Feedwater System
Engineered Safety Auxiliary Power System
Diesel Auxiliary Power and Support Systems
Residual Heat Removal System
Instrumentations and Power Sources for Various Systems and Components
Component Cooling Water System
Service Water System
Pumps and Motors for Lake Intake Water
Reactor Protection System

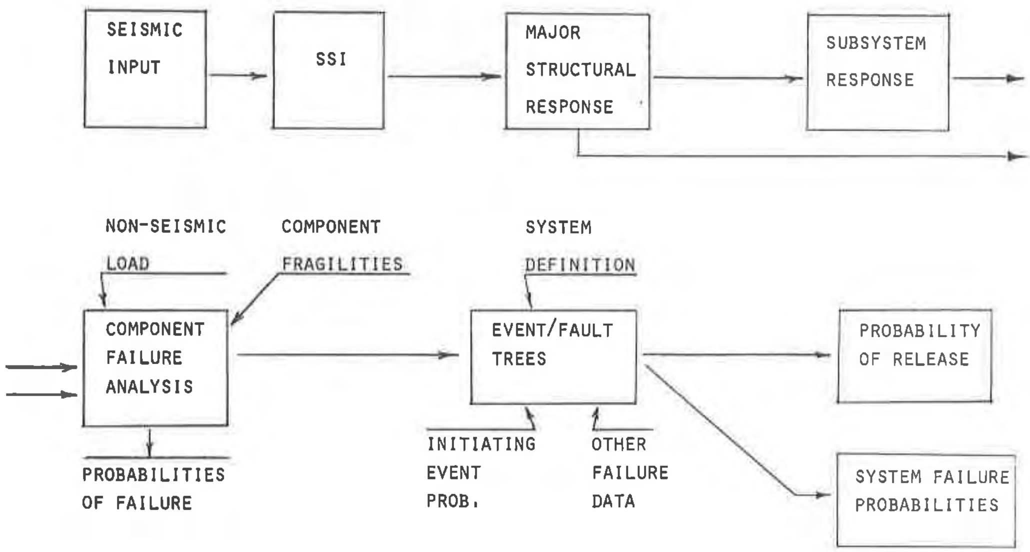

Figure 1. Schematic drawing of overall systems model.