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SEISMIC RISK ASSESSMENT OF A BWR: STATUS REPORT

T. Y. Chuang, D. L. Bernreuter, J. E. Wells
Lawrence Livermore National Laboratory

J. J. Johnson
NTS/Structural Mechanics Associates

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T. Y. Chuang, D. L. Bernreuter and J. E. Wells

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Lawrence Livermore National Laboratory
Post Office Box 808
Livermore, California 94550

J. J. Johnson

NTS/Structural Mechanics Associates
Two Annabel Lane
San Ramon, California 94583

Abstract

The seismic risk methodology developed in the U.S. NRC Seismic Safety Margins Research Program (SSMRP) was demonstrated by its application to the Zion nuclear power plant, a pressurized water reactor (PWR). A detailed model of Zion, including systems analysis models (initiating events, event trees, and fault trees), SSI and structure models, and piping models was developed and analyzed. The SSMRP methodology can equally be applied to a boiling water reactor (BWR). To demonstrate its applicability, to identify fundamental differences in seismic risk between a PWR and a BWR, and to provide a basis of comparison of seismic risk between a PWR and a BWR when analyzed with comparable methodology and assumptions, a seismic risk analysis is being performed on the LaSalle County Station nuclear power plant.

I. Introduction

The Seismic Safety Margins Research Program (SSMRP) (Smith et al (1)) was a U.S. NRC-funded multiyear program conducted by Lawrence Livermore National Laboratory (LLNL). Its goal was to develop a complete, fully coupled analysis procedure (including methods and computer codes) for estimating the risk of an earthquake-induced radioactive release from a commercial nuclear power plant. The analysis procedure is

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based upon a state-of-the-art evaluation of the current seismic analysis and design process and explicitly accounts for uncertainties inherent in such a process.

The seismic risk methodology developed in the SSMRP was demonstrated by its application to the Zion nuclear power plant, a pressurized water reactor (PWR). A detailed model of Zion, including systems analysis models (initiating events, event trees, and fault trees), SSI and structure models, and piping models, was developed and analyzed. The SSMRP methodology can equally be applied to a boiling water reactor (BWR). To demonstrate its applicability, to identify fundamental differences in seismic risk between a PWR and a BWR, and to provide a basis of comparison of seismic risk between a PWR and a BWR when analyzed with comparable methodology and assumptions, a seismic risk analysis is being performed on the LaSalle County Station.

Key elements of the analysis are:

- Development of the systems models -- event and fault trees.
- Benchmark best estimate seismic response of structures, components, and piping systems with design values for the purposes of specifying median responses in the seismic PRA.
- Develop building and component fragilities for important structures and components.
- Investigate the effects of hydrodynamic loads on seismic risk.
- Perform seismic risk calculations.

Seismic risk analysis can be considered in five steps: seismic hazard characterization (seismic hazard curve, frequency characteristics of the motion); seismic response of structures and components; structure and component failure descriptions; plant logic models (fault trees and event trees); and probabilistic failure and release calculations.

LaSalle County Station is located in the agricultural area of Brookfield Township, LaSalle County, Illinois. It is approximately 55 direct-line miles southwest of Chicago and 20 miles west of Dresden power station. The station utilizes two single-cycle forced-circulation boiling water reactors, each rated at 3293 Mwt and designed for 3434 MWt. The gross electric output of each unit is 1122 MWe; the net output is 1078 MWe from each General Electric (GE) turbine-generator. The NSSS supplier was GE (Nuclear Energy Division).

The containment design employs the BWR Mark II concept of over-under pressure suppression with multiple downcomers connecting the reactor drywell to the water-filled pressure suppression chamber. The primary containment is a steel-lined, post-tensioned, concrete enclosure, housing the reactor and the suppression pool. This primary containment is entirely enclosed in the reinforced concrete reactor building which is the secondary containment structure. The power generation complex includes several contiguous buildings-two reactor buildings, an auxiliary building (housing the control room), the turbine building, diesel-generator buildings, the radwaste building, the service building, and the off-gas building.

2. Development of the Seismic Input

For the LaSalle site we developed the seismic input in a manner similar to the approach we used for the Zion site (Bohn et al (2)). The hazard curves were developed using a much improved analytic approach (Bernreuter et al (3)), as compared to the methodology used for the Zion. However, the basic concept remains the same. Two expert panels were formulated, one dealing with the seismicity parameters such as zonation and earthquake recurrence models. The second panel dealt with ground motion models and correction for local site effects on the predicted ground motion. The new methodology employed a simulation approach to perform the uncertainty analysis. Each expert's (both seismicity and ground motion) input was kept intact and a total of 2750 simulations were performed for the LaSalle site. Each simulation is a complete hazard curve. The 2750 simulations were aggregated into constant percentile hazard curves using the regional self weights provided by the experts.

Following the Zion analysis approach (Bohn et al (2)), the hazard curves were developed at a hypothetical rock outcrop. A set of rock outcrop time histories were developed consistent with the hazard curves, i.e., having the correct proportion of earthquakes with magnitude m_b and distance R as dictated by regional tectonics.

3. Seismic response of structures and components

For each level of earthquake described by the seismic hazard curve, three aspects of seismic response are necessary to perform the seismic risk analysis: median level (or best estimate) response, variability of response, and correlation of responses. Seismic responses are required for all structures and components contained in the plant logic models. The three aspects of seismic response are discussed:

- Median level response - the median level response given an earthquake occurrence is needed. In general, this median level response differs from the design values because, in the latter case, design analysis procedures, parameter selection, and qualification procedures are conservatively biased.

- Variability of response - variability in seismic response resulting from variations in the earthquake excitation, the physical properties of the soil/structure/piping system, and our ability to model them must be acknowledged and included in the seismic risk analysis to permit calculation of probability of component failure and core melt frequency.
- Correlation of responses - the tendency for pairs of responses to have simultaneously high or low values results from two sources -- the level of the earthquake and the dynamic characteristics of the system. The level of the earthquake affects correlation since a large earthquake (large peak acceleration) may cause all response to be large, whereas, a small earthqauke produces the opposite effect. The second source of correlation is due to system response itself. For example, floors within a structure may all experience high values of response simultaneously due to the dynamic characteristics of the structure itself.

Three approaches to developing median level response are possible: re-calculation using best estimate methodology and parameters such as was done in the SSMRP; use design responses scaled to account for conservatisms introduced in their development; and a combination of the two, i.e. a limited amount of re-calculation of response using best estimate methodology and parameters is performed and scale factors developed to be applied to design responses. The latter case is being applied to the LaSalle County Station seismic PRA.

The basic strategy for developing median level responses was to perform selected probabilistic response analyses of the LaSalle County Station structures for two ranges of earthquakes -- a lower level earthquake in the approximate range of the SSE and a higher level earthquake two-to-three times the SSE. Results of the analyses were probability distributions on two types of response -- in-structure forces and moments to be used in the fragility evaluation of the structures themselves; and in-structure response spectra at equipment and component locations for their fragility evaluation. Two acceleration levels were considered to permit interpolation for other earthquakes of different peak accelerations. Each element of the probabilistic response analyses is discussed:

- Seismic hazard. The seismic hazard for the LaSalle site is specified on a rock outcrop due to the presence of a shallow soil layer (approximately 170 ft.) overlying the stiff bedrock. Local site amplification was taken into account explicitly as described below. Specifying the seismic hazard for the purpose of the seismic PRA entailed specifying the hazard curve -- the probability of occurrence of an earthquake of a given peak ground acceleration including magnitude and distance characteristics, and the frequency characteristics of the motion -- an ensemble of acceleration time histories (three components per earthquake simulation) on the rock outcrop.

- Local site amplification. Using equivalent linear viscoelastic soil properties developed as a function of earthquake excitation level and the assumption of vertically propagating waves, earthquake motions on the soil surface were developed for response prediction. This representation of local site amplification is a source of modeling uncertainty.
- Soil-structure interaction (SSI) parameters. The soil configuration and low strain soil properties were established based on the boring logs and soil reports for the LaSalle site. Nominal soil properties as a function of excitation level were estimated from a series of SHAKE analyses using rock outcrop motion as input and material property variations vs. strain relations developed by the geotechnical engineer for the utility. SSI parameters (foundation impedances and scattering matrices) were developed for the important LaSalle buildings using the CLASSI programs. The LaSalle structure analyzed in detail is a single complex structurally which contains the reactor building, the auxiliary building, the turbine building, off-gas filter building, and diesel generator buildings. An average embedment of approximately 51 ft. was treated in developing the SSI parameters.
- Structure model. Structure models developed by the utility and used in the design seismic analysis were used in the probabilistic response analyses. Fixed-base eigensystems for the horizontal and vertical models were developed by the utility for use in the analyses. The SMACS methodology of the SSMRP (Johnson et al (4)) through the structure response phase was used here. SSI is treated by the substructure approach.
- Response analyses. SMACS analyses were performed on the LaSalle structure complex including the effects of SSI. SMACS links together seismic input, SSI, structure response, and piping system and component response. All aspects except piping system response were treated here -- component response was determined from in-structure response spectra. Variability is treated in SMACS. Ensembles of three component acceleration time histories define earthquake variability. Variability in SSI and structure response is treated by varying a discrete number of input parameters of the soil and structures (soil shear modulus, soil material damping, structure frequency, and structure damping). SMACS performs repeated deterministic analyses, each analysis simulating an earthquake occurrence. By performing many such analyses and by varying the values of the input parameters, uncertainty in deterministic analyses is taken into account. The discrete input

parameters were assigned variability described by lognormal distributions and sampled for each earthquake simulation. The Latin hypercube experimental design was used. For the LaSalle SMACS analyses, random variation in the parameters was considered. Thirty earthquake simulations were treated at each excitation level. Forty-eight in-structure response spectra were calculated for equipment and component fragility assessment. One hundred-and-forty-five structure forces and moments were calculated for structure element fragility assessment.

4. Structure and component fragilities

The development of structure fragilities proceeded as follows. A review of the seismic design analysis results and development of a preliminary set of structure element capacities initiated the task. Simultaneously, a preliminary SMACS analysis was performed for a single earthquake simulation at near the SSE level to provide a basis of comparison with the design results. Having reviewed the design analysis results and structure model, changes in the structure model to better capture the expected behavior of the structure were recommended and incorporated into the SMACS analysis. Additional preliminary SMACS analyses were performed, loads generated, and an assessment of the model modifications made. The initial model changes led to limited load redistribution and motivated a second set of model changes which were incorporated into the SMACS model and again evaluated. The result was the best estimate structure model. One hundred-and-forty-five structure forces and moments at two excitation levels were obtained from the SMACS analyses and used in the fragility development. Component fragilities were developed for major LaSalle components identified as important in terms of systems behavior and risk. LaSalle specific design reports and equipment qualification data were used as the principal basis for fragility assessment. Median level responses were used in the fragility assessment as generated from the SMACS analyses.

5. BWR hydrodynamic loads

A limited investigation of the effects of internally generated hydrodynamic loads on the seismic risk is underway. This effort concentrates on SRV discharge as the most likely loading condition and considers its effect on components and equipment. Realistic best estimate treatment of the phenomenon is emphasized along with an approximate load combination methodology to be applied to hydrodynamic and seismic loads.

6. Seismic Risk Calculations

The seismic risk calculations for LaSalle BWR will be similar to those performed during the Zion seismic risk assessment (Bohn et al (2)). The calculations of the frequencies of core-melt due to radioactive release are performed using the SEISIM computer code (Wells (5)). The capacity to handle dependent failures having any degree of correlation is what sets SEISIM apart from any other existing quantitative risk assessment code.

The calculations of radioactive release frequencies requires us first to identify the seismically-induced initiating events which require shutdown of the reactor. Then the potential accident scenarios leading to core melt and radioactive release, which could occur following an initiating event, are hypothesized and characterized by event trees (Garcia et al (6)). Failure modes for the safety and auxiliary systems are identified and expressed in terms of fault trees (Barlow et al (7)) for each system. Quantifications of the event and fault trees yield boolean expressions which specify the logical relationships between failures of structures, piping, and components that can lead to core melt. These logical relationships are input in the form of minimal-cut-set expressions that define the failure modes of systems in terms of their basic events. The SEISIM code was designed to compute the probabilities of the accident sequences by computing the probabilities of the minimal cut sets that define the accident sequences.

SEISIM uses the response data and fragility functions to compute the failure probabilities of structures and components, to calculate system failure probabilities, initiating event probabilities, accident sequence probabilities, and radioactive release frequencies.

Two sets of fault trees are being used in the analysis. One set is less detailed than the other. The less detailed set was developed at LLNL while the more detailed set was developed on the Risk Methods Integration and Evaluation Program (RMIEP) (Kolb et al (8)). We have transmitted on to the RMIEP those specific items that are seismically related and provided a culling criteria. The RMIEP then used this culling criteria to solve the fault trees and accident sequences and then transmitted that information on to LLNL. This information will then be combined with response and fragility information to obtain the frequencies of radioactive release and an importance ranking of components within the LaSalle County Station that are susceptible to the seismic event. The results of the two sets of fault trees will then be compared.

The analysis of the initiating event probabilities is different in the seismic case. To generate the probability of occurence of an initiating event, a boolean expression is developed which represents the combination of pipe breaks and other failures that can cause a break equivalent to the specified size. The general categories of concern are those in which transients occur, those which you have a loss of coolant and automatic depressurization is required, and those which you have a loss of coolant which causes depressurization. The boolean expressions developed for these situations are then input into the SEISIM computer code and probabilities of occurence are generated. Only single and double events are considered when computing the initiating occurence probabilities.

The analysis of the accident sequences includes all the same events as are appropriate for an internal event analysis. These include maintenance errors, operator errors, and other failures that are not specifically related to the seismic event. The importance analysis studies all these factors when generating its importance ranking. The importance measure of components is related to the Vesely-Fussell measure (Lambert (9)). This measure is an approximation to the actual importance of independent components because of the sum of cut set probabilities is an upper bound on the probability of the union of cut sets containing a component.

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