Validation Needs of Seismic Probabilistic Risk Analysis (PRA) Methods Applied to Nuclear Power Plants

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ABSTRACT

An effort to validate seismic PRA methods is in progress. The work concentrates on the validation of plant response and fragility estimates through the use of test data and information from actual earthquake experience. Validation needs have been identified in the areas of soil-structure interaction, structural response and capacity, and equipment fragility. Of particular concern is the adequacy of linear methodology to predict nonlinear behavior. While many questions can be resolved through the judicious use of dynamic test data, other aspects can only be validated by means of input and response measurements during actual earthquakes. A number of past, ongoinging, and planned testing programs which can provide useful validation data have been identified, and validation approaches for specific problems are being formulated.

1. INTRODUCTION

Seismic PRA methods have been applied in recent years to clarify safety issues for nuclear power plants [1]. The reason for this is the realization that seismic events can affect many plant systems simultaneously, and therefore, can be a significant or even dominant contributor to overall risk. The randomness of the seismic hazard, the uncertainties and variabilities of the needed data, and the approximate nature of the methodology raise questions of credibility with respect to the results of seismic PRAs. This, in turn, leads to questions as to the conclusions that can be drawn from the results concerning safety implications and regulatory actions. While the ultimate answer to these questions depends on the intended end-use of seismic PRAs, it is nevertheless useful to attempt to validate the methodologies.

Seismic PRAs are performed at different levels of sophistication and detail [1,2], but in general, in all analyses three aspects are considered and technical information is sought in three areas as inputs to a seismic PRA; these are:

- Definition of the seismic hazard at the site,
- Description of the plant response and fragility,
- Description of plant failure scenarios and consequences.

A calculation procedure assembles this information to produce the results of the PRA, i.e., estimates of risk. Thus the seismic hazard, given usually in terms of a functional relationship between probability and site acceleration, is used to determine spacial distributions and accelerations at the plant foundation. The susceptibility (fragility) of the nuclear power plant subjected to the seismic excitation is then determined. In its most general form this estimate requires a response analysis of the soil-structure systems, to establish among other things the base motion at component supports. Also needed are predictions of component response, and a determination of component fragilities and structural capacities. This includes descriptions of the level and parameters of the seismic hazard which cause vital plant components and systems to fail as well as the definition of expected failure modes. The final aspect of the seismic PRA is the systems analysis which defines accident scenarios and consequences, and provides estimates of risk. All of the parts of seismic PRAs contain stochastic elements, and all of them are in need of validation. Here effort is primarily focused on the validation of methods and data which are used to determine plant response and fragility. However, cognizance must be taken of the interrelationships to other seismic PRA elements.

The current effort is concerned with the validation of the seismic PRA method through the use of data from testing. The term "testing" is used here in a broad sense and includes data from specific laboratory and field experiments as well as measurements obtained from earthquakes or other natural environments. The immediate objective is to assess the potential of using test data, in the areas of plant response and fragility, to improve modeling of phenomena and predictive capabilities and thus to build confidence, enhance the understanding, and improve the utility of the results of seismic PRAs.

2. VALIDATION NEEDS AND PRIORITIES

The assessment of validation needs for seismic PRA methods includes both the determination of verification requirements for the calculational procedures and the identification of deficiences in data bases. Of particular concern is the adequacy of linear analysis, which is generally used, to predict the expected nonlinear response of structures and components under seismic loading. Also of interest is the assessment of response variability caused by uncertainties in input parameters and by variabilities in analysis methods. Identification of the needed fragility data for structures and components is also a major concern, and the probabilistic aspects of the information is considered.

Identification of PRA validation needs without consideration of the relative importance of the selected items leads to the identification of "soft spots" in the methodology. Ranking of potential validation tasks according to measures of how much their successful execution contributes to increasing the usefulness of seismic PRAs can significantly enhance the results. Thus, three steps were used to determine priorities and focus on the most effective research. First, elements of seismic PRAs that are amenable to validation by experiments or existing data were identified. Second, criteria were selected for assessing the potential benefits of experiments for improving the utility of seismic PRAs. Finally, an evaluation of the utility of testing based on these criteria was performed.

2.1 Items Requiring Validation

While many specific items in need of validation were identified [3], they all fall into the following categories: soil-structure interaction (SSI), structural response and capacity, and component and equipment fragility. Seismic response of the soil-structure-component system is important in two aspects. First, the soil-structure system or component is intended to perform its design (safety) function during and after an earthquake. Second, the soil, structure, and subsystem also act as transmitters and filters of vibratory motion thus modifying the loads transmitted to safety systems whose fragility is of interest. The key question is: Given an earthquake described by its seismic hazard curve parameters, what are the median (mean) level of seismic response, variability of responses, and correlation of seismic responses? The variability of seismic response addresses the major stochastic aspect of seismic PRAs, and response correlation deals with the system characteristics which lead to responses of like intensity throughout the plant. The validation effort must address all these aspects of seismic response. Among the inputs required for seismic PRAs are estimates of failure data and descriptions of damage mechanisms for structures, equipment and components. Again these component fragilities and structural capacities are subject to variabilities due both to randomness and uncertainty and validation of all aspects is of interest.

2.2 Ranking of Validation Needs

The following set of criteria was used to help prioritize the choices of seismic PRA validation needs:

- Significance as indicated by past earthquake experience
- Significance as indicated by past seismic PRAs
- Contribution to common mode failures
- Contribution to uncertainty in risk
- Potential for reducing modeling uncertainties
- Contribution to uncertainty in loads
- Potential for simplification in methods and models
- Applicability to a large number of plants

No claim is made that the above criteria are all inclusive. However, they cover most of the problem areas concerning current PRA methodology. The first six criteria deal with improving the results of seismic PRAs and with confidence building. The last two criteria are concerned with streamlining the analysis procedures, a worthwhile goal in itself considering the large effort required in performing seismic PRAs.

Each of the seismic PRA elements identified as a candidate for validation [3] was assessed in light of the above criteria. Using a simple ranking scheme a judgment was made if additional information or data, i.e., validation by testing, in this area would contribute significantly to improving seismic PRAs as expressed in each of the specific criteria. Detailed results of this evaluation are presented elsewhere [3]. While this preliminary evaluation and the ranking procedure are in need of refinement, they nevertheless provide some indication of the importance of the seismic PRA elements identified for validation. The areas of highest priority for validation are:

- Soil-Structure Interactions
- Capacity/Failure of Structures
- Equipment Fragility
- Structural Response
- Variability of Response
- Spacial Variation of Free-Field Motion

3. VALIDATION THROUGH TESTING

Since testing in general requires large resources, it is imperative that prior to making specific test recommendations all available existing data from tests and earthquakes, be reviewed as to their appropriateness for validation of seismic PRAs. Where possible, participation in ongoing or planned experimental efforts that could provide some of the needed data should be explored.

At this juncture two large scale testing programs have been identified as possible sources of data for Seismic PRA analysis validation. These are: The HDR Program [4] conducted by the Kernforschungszentrum Karlsruhe (KfK) in the Federal Republic of Germany (FRG) and the planned earthquake testing of a 1/4 scale containment by EPRI in Taiwan [5]. Though the HDR tests will use excitations by a large shaker on the operating floor, significant rocking of the entire structure is expected so that at least some aspects of soil-structure interaction (SSI) and structural response analyses may be verified. The HDR facility contains also a number of piping systems and much nuclear plant equipment all of which will be subjected (directly or indirectly) to high levels of excitation during the Phase II tests. This provides a multitide of opportunities for analysis validations. The 1/4 scale containment experiment in Taiwan is specifically designed by EPRI to provide data for SSI analysis verification and should indeed be very useful for validating this aspect of seismic PRAs. The major drawback of this test program is that one has to await the earthquakes. Since downhole instrumentation will be provided, the earthquake experiments in Taiwan should also yield information on the spacial variation of free field motions and can thus serve the validation of deconvolution techniques used in estimating that variation.

3.1 Testing to Validate Soil-Structure Interaction (SSI)

Testing suitable to establish the validity of SSI analyses must be conducted with systems that are of sufficient size to somewhat simulate prototypic behavior, i.e., frequency response, magnitude of motions and gravitational effects similar to those of the actual nuclear power plant structures. Small scale testing for the verification of SSI analyses is not very satisfactory, since scale effects may mask some salient behavior while exaggerating other phenomena. While excitation through the ground similar to an earthquake is preferable, some features of the SSI analysis may be evaluated for other loading, e.g., by shaker, as long as the SSI response is significant. The latter is necessary regardless of what testing approach is used and it is preferable that the motion be sufficiently strong to induce nonlinear effects so as to challenge the analyses which use equivalent linear methods. The test data used in SSI analysis validation should also provide information on the adequacy of the substructuring approach used in most calculations. Both the HDR tests [4] and, in particular, EPRI/Taiwan experiments [5] should be valuable in validating SSI analyses.

Soil failure and liquefaction as well as basemat uplift have been simulated under testing conditions, e.g., high explosive testing, weapons testing, and centrifuge experiments. Data from such testing will at most provide qualitative insight and define error bounds of analyses which neglect these phenomena. The data may also permit improvement in the determination of impedance functions and damping values for soils prone to failure. However, data from such testing should be used with great caution because of the difficulties of scaling such effects.

3.2 Testing for Structural Analysis Validation

Validation of the response analyses for large structures, components and piping used in seismic PRAs should include benchmark type tests for each of the subsystems separately and also for integral structure/component/piping configurations. Response levels in the testing should extend well into the nonlinear and plastic regime to bound the errors expected from the linear equivalent analyses. Tests for piping should include base motion excitation. To really challenge the analyses procedures structural configurations of significant complexity are needed. Here again the Phase II HDR shaker tests [4] with high accelerations and large displacements may play a significant role. Also the 1/4 scale containment earthquake experiments to be conducted in Taiwan under EPRI sponsorship [5] should be of value. While the structure is simpler than a real power plant, it will contain a large componment (steam generator) and piping to provide sufficient complexity to challenge the structural analysis methods.

3.3 Testing to Validate Response Variability and Correlation

Variations in earthquake excitation cannot be addressed by dynamic testing and one must rely on collecting more complete earthquake information. To estimate variability of response due to variations in physical properties and soil/structure parameters, e. g., shear moduli and damping values, multiple testing of reasonably complex systems under various loads is required. It is most cost effective to validate variability of response by analyzing data from structures which for other reasons are subjected to multiple testing or earthquake excitation. Similarly, if a number of analyses with models of varying complexity were used to predict the response of such systems and/or if different analysts performed such calculations, each with his own model, a measure of the expected modeling variability could be obtained. Should such a structure also contain a number of equipment items in a generic category, e.g., many valves, it should be possible to obtain some measure of response variability for given equipment categories. Validation data for correlation of seismic response can again only be obtained from multiple testing of large complex structures preferably containing a significant number of equipment items. Excitation in these tests should be random with significant ground shaking being the preferred method.

The HDR plant system (which is well instrumented) was subjected to a variety of loadings during Phase I [6] of its test program and will experience multiple loadings at higher excitation levels during Phase II [4] testing. Thus, the analysis of past and future HDR tests in the light of seismic PRA requirements, should provide good insight into the variability of response and physical properties of complex reactor systems. Similarly the HDR tests can be used to evaluate modeling variability by using past and future predictive analyses performed in conjunction with the tests. Since HDR contains many equipment items belonging to single generic categories, the possibility of obtaining variability estimates for the response in a generic group of equipment exists.

3.4 Testing to Validate Structural Capacity and Failure

There is a need to assess the effect of neglecting the geometrical and material nonlinearities in seismic PRAs and to establish the modes and levels of failure for concrete and steel structures. In view of the coupled uncertainties in damping, modeling, material properties, ductility, etc., it is difficult to devise tests for validation.

Since ductility factors are used in determining the capacity of concrete structures it is essential that validation testing be done at least at the level of incipient failure and with subassemblies which include the proper boundary conditions, e.g., box structures. Testing to failure of as-built structures is, in general, not feasible, unless a well instrumented structure experiences failures during an earthquake event or can be sacrificed. While the response and failure of models subjected to severe loading may not be prototypic, such testing may provide information on possible failure modes and may be helpful in validating computational approaches.

3.5 Testing to Validate Component and Equipment Fragility

To define the fragilities, i.e., probability of failure vs. load level, and the descriptions of failure mechanisms for nuclear power plant equipment, it is best to rely on separate effects tests such as shake-table experiments. To obtain such data for the multitude of plant equipment is an extremely costly undertaking. Therefore to reduce this effort, existing data, even if not fully applicable, should first be evaluated. Next the components most important to plant safety and whose failure has a large contribution to risk must be identified and testing must concentrate on these items. Where available, use should also be made of equipment qualification data. While the applicability of these data is limited, it may nevertheless define the tail end (at low level of excitation) of the fragility curve. Similarly experience data from actual earthquakes should be used. However, this data base is limited and documentation often is poor.

For piping it is essential to obtain failure data for total piping systems (including pipe runs, supports, nozzles, components, anchors, branch connections, etc.) and for a variety of piping configurations. Once knowledge is gained concerning overall failure mechanisms, it may be most cost effective to proceed with separate effects testing in those areas indicated to be most critical to failure. High level testing of integral facilities are needed to discover oversights in seismic PRAs regarding interactions of interfaces and boundaries between structures and components, between walls and penetrations, between piping and components, etc. If particular boundary effects are found, then it may be best to quantify these through supplemental testing that includes boundary modeling.

The HDR large shaker testing appears to present favorable conditions under which boundary and interface effects may be discovered. Higher excitation levels will be achieved in the HDR tests when direct loading will be applied to piping systems by hydraulic actuators. Testing to failure and/or pipe plastification will take place. To make these experiments meaningful for the validation of piping fragility, careful experimental design is necessary so that failure is not dictated by the method and location of load application.

4. CONCLUSIONS

Needs for validation of the response analysis and fragility estimates used in nuclear power plant seismic PRAs exist in the areas of soil-structure interactions, structural response and capacity, and equipment fragility. While large uncertainties also exist in the seismic hazard definition and validation of seismic PRA system analysis is also necessary, these areas are not addressed in the current effort. It is thought that much useful validation information can be obtained from dynamic testing of structures and components. However, some information is only obtainable through the monitoring of structures subjected to earthquake excitations. Because of the expected high cost of testing, all existing data should be reviewed as to their applicability to the validation tasks. Similarly, every effort should be made to participate in ongoing or planned experimental studies which may yield validation data for seismic PRAs.

Two major testing programs promise to provide significant information for the validation of seismic PRA methods. First the HDR Program [4] should yield data for the validation of response analyses and in particular for the evaluation of the adequacy of linear analyses in representing nonlinear response and the interactions of complex plant systems. Further, the existing and expected HDR data will be useful in evaluating response variability due to parameter and modeling uncertainties. The second program of interest is the EPRI earthquake testing in Taiwan of a 1/4 scale containment [5]. This should provide data for the validation of all aspects of soil-structure interactions and related analysis methods, including deconvolution techniques, substructuring approaches and the adequacy of linear analysis. Further these tests should provide information on the spacial variation of free field excitation. Careful planning and prioritizing of specific validation tasks is necessary to take full advantage of all existing and expected test data.

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