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SEISMIC PROBABILISTIC RISK ASSESSMENT AND SEISMIC MARGINS STUDIES FOR NUCLEAR POWER PLANTS

by

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ABSTRACT

This report presents a review of the seismic probabilistic risk assessment and seismic margins studies for nuclear power plants in the United States. The techniques employed in these studies are briefly described. A few comments on the evaluation of the fragility of structures and equipment are discussed. Seismic PRA is a systematic process to evaluate the safety of nuclear power plants. In the process, it integrated all the elements such as seismic hazard, component fragility and plant system. Thus, it provides the overall view of the safety of an entire plant under a seismic event.

The major tasks of a seismic PRA such as the evaluation of hazard curves, component fragility and plant system are also present in probabilistic analyses of non-nuclear facilities. The concept and technique embodied in seismic PRA for nuclear power plants can be applied to other types of engineering facilities.

TABLE OF CONTENTS

SECTION 1
INTRODUCTION

Seismic analysis and design of nuclear power plant facilities is performed according to pertinent codes and specifications. For example, nuclear power plant structures are designed by using the various standards developed by ASME [1], ACI [2], AISC [3], etc. and the Standard Review Plan (SRP) [4]. These specifications are usually in a deterministic format. In order to assure the safety of structures, margin of safety or conservatism is incorporated in each design step. The specifications of design basis earthquakes, (Safe Shutdown Earthquake or Operating Basis Earthquake), the modeling of soil, structures and piping systems, the technique for response analysis, and formula for combining various static and dynamic loads are all incorporated a significant built-in conservatism. The conservatism introduced in the design and analysis procedure is usually determined by a working group of a code committee on the basis of collective engineering judgement. Facilities designed by such a procedure is usually safe; however, the margin of safety or the total conservatism during the service lives of nuclear facilities is not explicitly quantified. The question of margins becomes more critical if the design loads or the design criteria have been changed. For example, the Safe Shutdown Earthquake (SSE) in the eastern United States may need to be increased; thus a decision on whether or not to upgrade the existing nuclear power plants depends on the actual margins against the new specified SSE.

The conservatism mentioned above is intended to cover randomness and uncertainty arisen from the operation of nuclear facilities. It is well recognized that earthquake loads as well as other static and dynamic loads are random in nature. Even though the state-of-the-art in seismology has been improved, we still cannot predict the occurrence of an earthquake in advance nor estimate precisely the characteristics of earthquake such as magnitude, duration and frequency content of the strong ground motion. Similarly, the structural resistance (or capacity) cannot be determined exactly. The structural resistance is a function of many basic variables. These variables such as the material strengths and geometry of structures exhibit some statistical variations. In order to take the randomness and uncertainty in loads and structural resistance, etc. into consideration in the risk assessment, a probabilistic approach is a rational choice, since the theory of probability provides a framework for the formal treatment of uncertainties.

In recent years, the nuclear industries in the United States and the regulatory authority, i.e., U.S. Nuclear Regulatory Commission (NRC) have made a tremendous effort to assess the safety of nuclear power plants. In addition to the Systematic Evaluation Program (SEP) [5], which intends to upgrade the oldest nuclear power plants in the U.S., two other major programs are seismic probabilistic risk assessment (PRA) and seismic margins evaluations. In this report, the PRA studies carried out by nuclear industries and the NRC are reviewed first. Fragility evaluation methods proposed by utilities and research groups are discussed in detail. Then, the seismic margins programs conducted by NRC and Electric Power Research Institute (EPRI) are described.

SECTION 2
SEISMIC PROBABILISTIC RISK ASSESSMENTS

The purpose of performing a seismic PRA study is to estimate the probability of core melt and radioactive release from a nuclear power plant due to earthquakes. The seismic PRA studies were conducted for about 20 nuclear power plants by utilities companies. In addition, the Seismic Safety Margins Research Program (SSMRP) [6,7] was carried out by Lawrence Livermore National Laboratory (LLNL) under the auspices of the U.S. Nuclear Regulatory Commission. The seismic PRA utilizes a systematic process which intends to take into consideration of all possible randomness and uncertainties in the operation of nuclear power plant facilities. In these studies, randomness means the variability inherited in loads or structures and components. Thus, it cannot be reduced. On the other hand, variability that is potentially reducible is defined to be uncertainty. The notion of separating variability into randomness and uncertainty is an idealized concept. In practice, the distinction of randomness and uncertainty usually becomes blurry. The major tasks in performing a seismic PRA study are as follows:

(1) seismic hazard analysis

(2) structure/equipment fragility assessment

(3) accident sequence analysis, and

(4) consequence (risk) evaluation.

The products of a seismic PRA study usually include the probability of core melt, early fatalities, late fatalities, and potential adverse health effect, etc. In addition, the dominant seismic risk contributors are also identified. In the following sections, each major task is briefly described.

2.1 Seismic Hazard Analysis

The earthquake hazard at a power plant site is described by a hazard curve, a plot of the probability of exceedence vs. the peak ground acceleration. The major elements of the seismic hazard analysis include: 1. Identification of the seismicity and sources of earthquakes, such as source zones and active faults. 2. Assessment of the expected occurrence rate of earthquakes with different magnitudes or epicentral intensities using either seismicity data or geological studies. 3. Development of attenuation relationships i.e. the reduction of seismic wave amplitude with distance. 4. Evaluation of local ground response. All the above information is integrated to generate the annual probability that the selected peak ground acceleration would be exceeded. Because of the large uncertainty in the seismic hazard analysis, a family of hazard curves is usually developed. Each curve is given a specified weight.

A complete seismic hazard analysis should also establish the characteristics of ground motions as well as a hazard curve. The earthquake ground motions can be represented by a response spectrum, a power spectrum or a set of time histories. In addition, the duration of strong ground motion also needs to be specified. The establishment of ground motion characteristics is a major problem in areas such as the eastern U.S. where very few strong ground motion recordings exist. At present, only the hazard analysis in the SSMRP program establishes the earthquake ground motions, while most of the seismic PRA studies performed by nuclear industries do not utilize the ground motions explicitly.

From most seismic PRA studies, it has been shown that a significant amount of uncertainty in the seismic PRA results is due to the seismic hazard estimates. Two major efforts [8,9] for evaluating the seismic hazard in the eastern United States are being carried out in order to reduce the uncertainties in the seismic hazard analysis.

2.2 Structure/Equipment Fragility Assessment

The fragility of a structure or an equipment is defined as the conditional probability of failure for a given value of a parameter. The majority of seismic PRA's performed to date uses the peak ground acceleration (PGA) as the parameter. If the peak ground acceleration is used as the parameter, the response analysis is included in the fragility evaluation.

The assessment of component (structure or equipment) fragility is a crucial task in a seismic PRA study. Accident sequences can be triggered by the occurrence of a severe earthquake. Fragility data determine how hard it is to pull this trigger. If the fragility data are overestimated or underestimated, the results of the accident analysis will be distorted and subsequently mislead the analysts, the regulatory authority and the public. The fragility assessment is discussed in the next chapter.

2.3 Accident Sequence Analysis

When an earthquake occurs, a nuclear power plant may have a transient due to a loss of its off-site power or a large loss of cooling accident (LOCA). Such an event induced by an earthquake is called an initiating event. An initiating event usually will trigger a sequence of other events which involve various plant systems designed for responding to the initiating event. Thus, for each initiating event, an event tree can be developed as shown in Fig 1. [10]. An event tree presents all possible accident sequences (scenarios) resulting from an initiating event. An accident sequence is terminated either by successful mitigation through use of safety systems or by reaching a core melt.

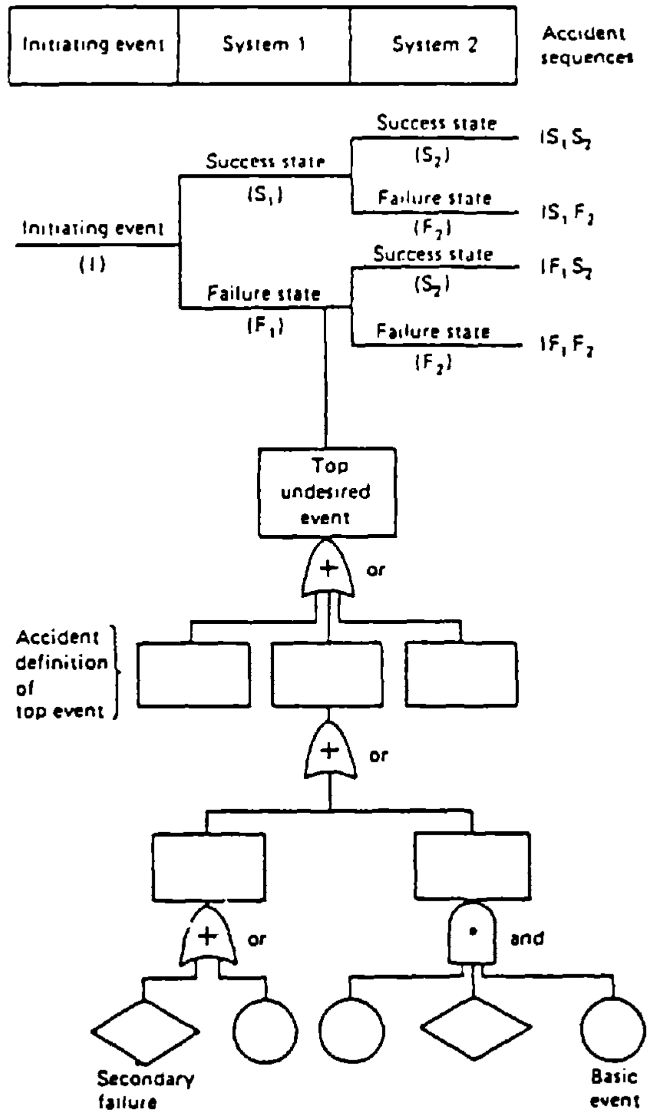
The success or failure of a system usually depends on the interrelationships and redundancies between many components. In addition, there may be more than one reason why a component or a system is unavailable. The unavailability of a system is represented by a fault tree, which depicts the logical relationships between the unavailability of the components in the system and unavailability of the system. A fault tree is also shown in Fig. 1. The probability of various core melts are calculated using the event/fault trees combined with the component fragilities and seismic hazard estimates. Then, the core melt probabilities are used in the containment failure analysis to determine the probability of radioactive release to the environment.

2.4 Consequence Analysis

Consequence analysis provides the final link in the PRA calculations and is intended to assess the effect to accidental releases of radioactivity on the surrounding population and the environment. The probability of release of radioactivity are combined with the site model, which includes weather data, population distribution etc., to obtain the probability of various adverse impacts. These adverse impacts include early and delayed fatalities, early and long-term injuries, contamination, and other economic impacts.

2.5 The Use of Seismic PRA

Seismic PRA is a systematic process to evaluate the safety of nuclear power plants. In the process, it integrates all the elements such as seismic hazard, component fragility, and plant system, and it takes into consideration the randomness and uncertainties in all these elements. Thus, it provides the overall view of the safety of an entire plant subjected to



An example showing event tree branching and levels of fault tree development.

Fig. 1 An Example of Event Tree and Fault Tree (Ref. 10)

a strong seismic events. By performing seismic PRA studies, the dominant contributors (accident sequences, systems, components etc.) to seismic risk can be identified. It also points out the weakness in plant design or operation. The results from a seismic PRA study can be used for the decision-making by authority, training of operators and plant staff, improving plant design including retrofitting, and planning of emergency preparedness.

SECTION 3
FRAGILITY ASSESSMENT OF STRUCTURES AND EQUIPMENT

Fragility data can be evaluated by using:

(1) Actual earthquake data

(2) Fragility or qualification test data

(3) Detailed analytical model

(4) Simplified analytical model

(5) Design information and engineering judgement

The most desirable fragility data are from actual earthquake experience or from tests, since such data (failure or success) provide information with high confidence. When earthquake and test data do not provide sufficient information, simplified or advanced analytical model may be used to predict failure of components. The model may include the randomness and uncertainties in the physical properties, the failure criteria and the model itself. The analytically constructed fragility curves should be verified with actual earthquake data, if available. The use of design information and engineering judgement is the most economical way to construct fragility data. However, the result may be very sensitive to subjective judgement, especially if it is based on the opinions of a few engineers. In the United States, several methods have been proposed for fragility evaluation [6,11-12]. These methods vary from that based on subjective judgement and design drawings to that based on probabilistic structural mechanics. Three of these methods are discussed briefly below.

3.1 Zion Method

The Zion method [11] was developed and applied to many industrial PRA studies such as Zion and Indian Point PRA studies [14,15]. In the Zion method, the fragility of a component is defined as the conditional probability of failure for a given peak ground acceleration. The main features of the method are : (1) the component fragility is assumed to be the product of several factors representing quantities such as capacity, ductility, and structural response. (2) each factor is assumed to be lognormally distributed. The median, expressed in terms of Factory of Safety (FS), and two logarithmic standard deviation values (one for randomness B_R and the other for uncertainties B_U), are primarily determined by the subjective judgement. Therefore, (3) the component fragility itself is also lognormally distributed. The median is obtained by a multiplication of the medians of the pertinent factors. The logarithmic standard deviations B_R and B_U are computed from the square root of the sum of square (SRSS) of the pertinent factors. As an example, Table 1 shows the fragility data of the Zion reactor building [14]. As shown in the table, the median acceleration is 5.1g which is 30 times the Safe Shutdown Earthquake (0.17g).

The Zion method is characterized by using engineering judgment to the maximum extent. Thus, it usually does not require detailed response and capacity analyses. However, the use of lognormal distributions for all variables is purely mathematical expedience. Furthermore, the subjective inputs and multiplication scheme do not appear to be a good combination. As a result, the fragility curve is very sensitive to the subjective judgements. As an illustration, suppose the fragility analysis shown in Table 1 is performed by another engineer. On the basis of his experience and judgement, he may think that the median factors of safety (FS) for both damping and combination of earthquake components should be 1.2 instead of 1.0. As the consequence, the estimated median acceleration becomes 12.2g as compared to the 5.1g originally estimated. The difference of FS between 1.2 and 1.0 is not unusual based on judgement; however, it has a tremendous effect on in the final result. The Zion method may be useful for a first-cut approach if performed by experienced engineers on an unbiased basis. However, almost all fragility assessments performed by utilities in the U.S. use the Zion method because it is the most economic way to construct the fragility data.

3.2 SSMRP Method

The SSMRP method [6] was developed under the NRC-funded Seismic Safety Margins Research Program . In this method, the fragility of a component is defined as the conditional probability of failure given a value of a local response (e.g., moment, stress, floor acceleration, etc.). The main features of this method are as follows:

1. A set of earthquake time histories are generated with a given peak ground acceleration which is the parameter used to describe the seismic hazard curve.
2. Randomness and uncertainty of the systems are represented by six parameters. Latin hypetube technique is utilized to generate the samples. Based on these samples,

TABLE 1 Fragility Data of Reactor Building (Ref. 14)

Structure: Reactor Bldg

Failure Mode: Flexural Failure of Containment Wall

Item	Median F.S.	B_R	B_U	B_C
Strength	7.2	0.14	0.15	0.21
Inelastic Energy Absorption	2.9	0.14	0.10	0.17
Spectral Shape	1.1	0.18	0	0.18
Damping	1.0	0.07	0.04	0.08
Modeling	1.0	0	0.18	0.18
Modal Combination	1.0	0.17	0	0.17
Combination of Earthquake Components	1.0	0.12	0	0.12
Soil-Structure Interaction	1.3	0	0.25	0.25
Total	30	0.35	0.36	0.50

Median Acceleration Capacity - 5.1g

structural and secondary system responses are obtained by using linear time-history analysis. The responses data are fitted to a lognormal distribution.

3. The capacity of a component and its associated randomness and uncertainties are estimated based on subjective judgement, lognormal distribution and limited test data.

4. The fragility curve of a component is then calculated based on the lognormal distribution of the response and capacity.

It is noted that in the SSMRP method, the distribution of a response is predicted through rigorous analyses (linear time history analysis and simulation technique), while the capacity is mostly based on judgements. The SSMRP method has also been applied to estimate the fragility data for the Zion nuclear power plant [16].

The SSMRP method makes a great effort to utilize the current techniques for response analyses. However, the use of time history analysis and Latin hypercube simulation technique [17] make the response analysis expensive. In view of this shortcoming, a simplified version of the SSMRP method has been proposed [18]. Essentially, the simplified SSMRP method proposes that the median response is estimated on the basis of the design calculation divided by a response factor, while the variabilities of the response is taken to be the same as those obtained from the Zion study [16] using the detailed SSMRP approach. To date, the author is not aware of any other PRA studies using this approach. This may be due to the fact that the SSMRP approach requires the computation of responses explicitly, which actually is the merit of the SSMRP approach.

3.3 RAS Method

The RAS method is a by-product of the Probability Based Load Combinations for Design of Category I Structures Program [13]. The program was sponsored by NRC and carried out by Brookhaven National Laboratory (BNL). The fragility curve is defined as the conditional probability of failure for a given peak ground acceleration, which is the same definition used by the Zion method. The BNL method derives the fragility curve of a component on the basis of a probabilistic structural analysis. The main features of this method are:

1. The earthquake ground acceleration with a given peak value is idealized as a segment of a stationary Gaussian process with zero mean and a Kanai-Tajimi spectrum. The

parameters of the spectrum are determined from the earthquake size and local soil conditions.

2. Power spectra of responses are obtained using model analysis and random vibration theory.

3. The distribution of the maximum response is established based on the extreme value theory of the stochastic process.

4. A limit state, which represent a failure mode, is analytically defined and a corresponding limit state surface is established. This limit state surface represents the capacity. Experiment data, if available are utilized in the establishment of the limit state surface.

5. The conditional limit state probability, i.e., probability of failure, is then computed by a reliability analysis. Thus, the fragility curve for a component is analytically generated. If the best estimated values (or mean values) for all the parameters are used to generate the fragility curve, the curve will be a mean fragility curve in approximation.

6. Randomness and uncertainty in the pertinent parameters are combined and characterized by appropriate distributions. Similar to SSMRP method, Latin hypercube sampling technique is utilized to include them in the fragility curves.

3.4 Comments on Fragility Assessment

As mentioned above, current methods proposed for fragility assessment vary from those based on subjective estimation to those based on analytical evaluation. The fragility evaluations must be made so that consistency and quality of results are ensured. In this regard, the following comments are presented.

Failure Modes

For PRA studies, the failure modes may be defined by component capacity or functional requirements. A component usually has many possible failure modes. For example, a structure may fail due to cracking, yielding, crushing, buckling, and drifting, etc. Since the purpose of a fragility assessment of a component is to predict how and where a component will fail and with what probability, it is essential to clearly specify the failure modes for each component. Unless failure mode is clearly defined, it is impossible to determine the capacity of a component, to choose a method for response analysis and to compare the results from different analyses of the same component. Identification of failure modes is also very important for collection of experimental data. If failure modes are not well identified, we may use irrelevant data for fragility evaluation resulting in erroneous conclusions. Unfortunately, in some of the fragility studies, definitions of the failure modes are only described in broad general terms. As a result, it is difficult to evaluate and compare the results.

Tail Region

Components in nuclear power plants are usually designed with highly conservative criteria. Thus, the chance of their failure is quite small even under extremely severe earthquakes. Thus, the lower tail of the fragility curve is most important in view of a realistic seismic hazard. As an example, Fig. 2 shows a hazard curve vs. a tangential shear fragility curve for an actual containment in the United States [19]. It can be seen from the figure that at a peak ground acceleration of 0.6g, which is already four times the Design Basis Earthquake (DBE), the probability of failure is still less than 1.0×10^{-6}.

In this respect, it is important to recognize that the tail part of a fragility curve is very sensitive to the assumptions of input variables. For example, Fig. 3 shows two fragility curves with the same statistics but different distributions (normal or lognormal). They are quite different in the tail region. This makes it critical which particular distribution function is assumed for fragility evaluation.

Effort for Fragility Analysis

It is sometimes asserted that component fragility curves need not be determined with precision in view of the large variations associated with the seismic hazard estimation. If this were true, the current effort, with aid of highly sophisticated analysis, experiments and field tests, to predict the response behavior of the components under seismic condition could be dismissed as cost-ineffective at best and totally useless at worst. The assertion could also imply that the current design criteria are unrealistically conservative. Furthermore, fragility estimates by different groups of engineers may vary considerably, especially in the lower tail region. For example, two fragility curves for a reinforced concrete containment with respect to tangential shear failure are shown in Fig 4. [15,19]. Significant

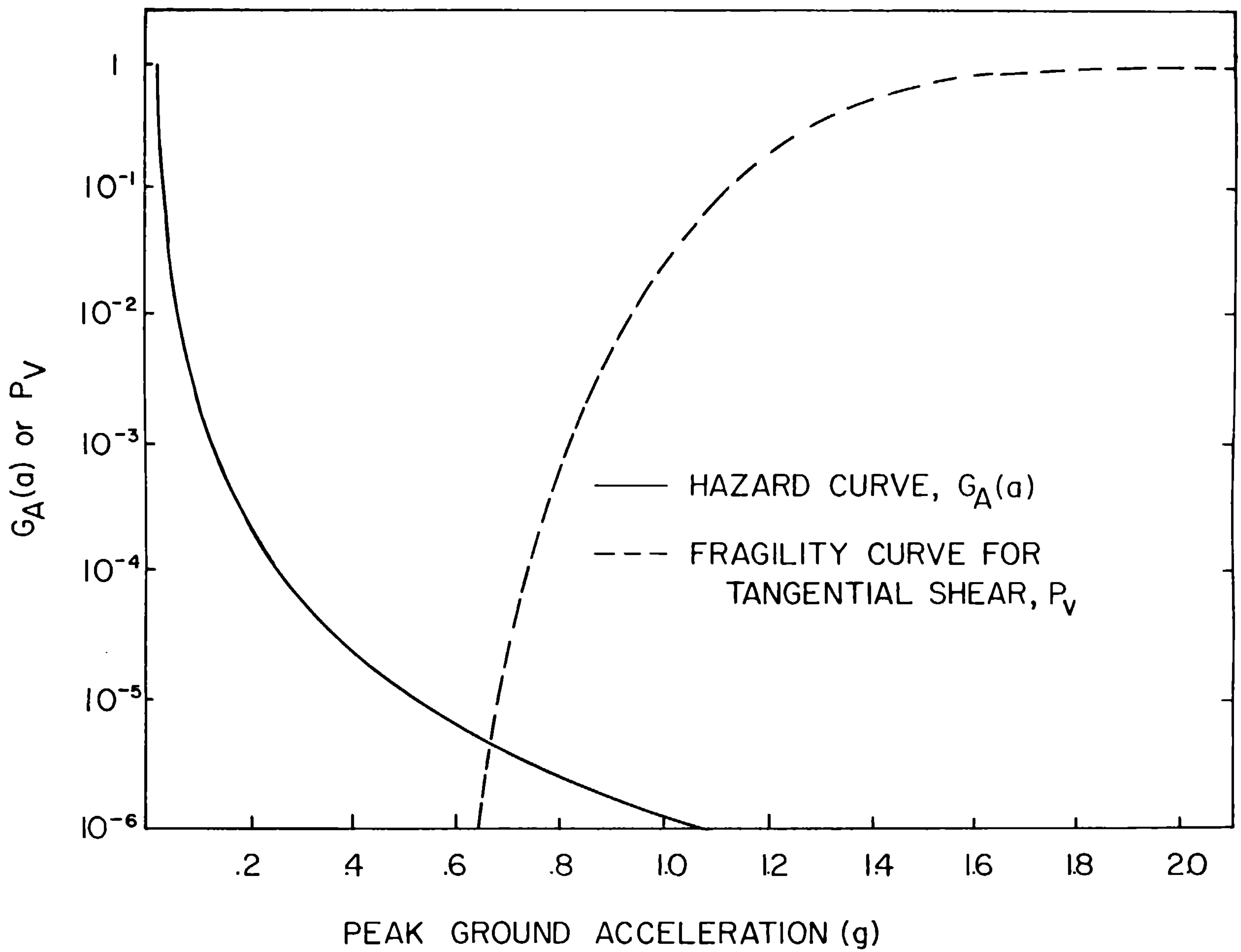


Fig. 2 Hazard Curve vs. Containment Tangential Shear Fragility Curve

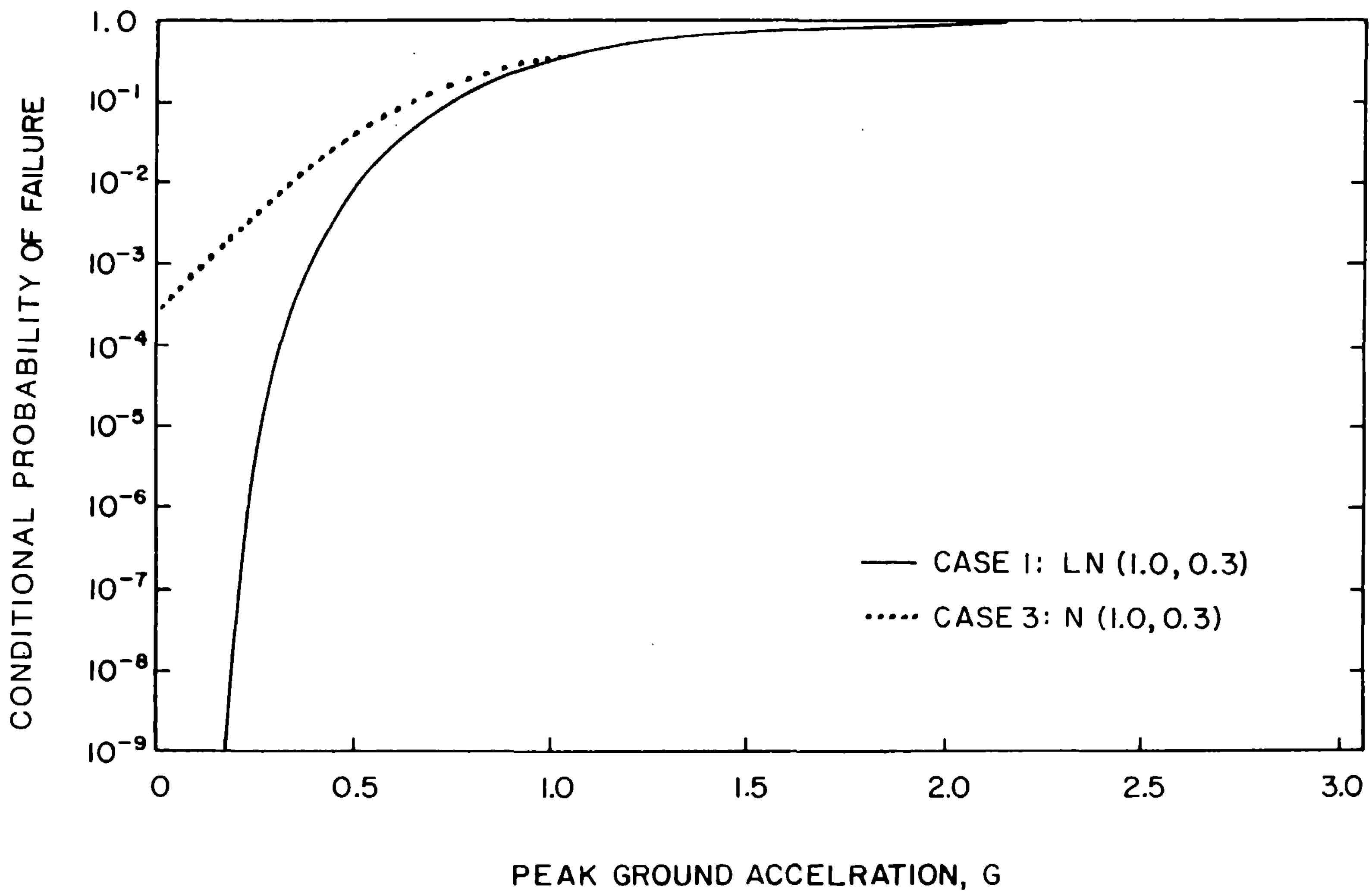


Fig. 3 Fragility Curves with Lognormal vs. Normal Distributions

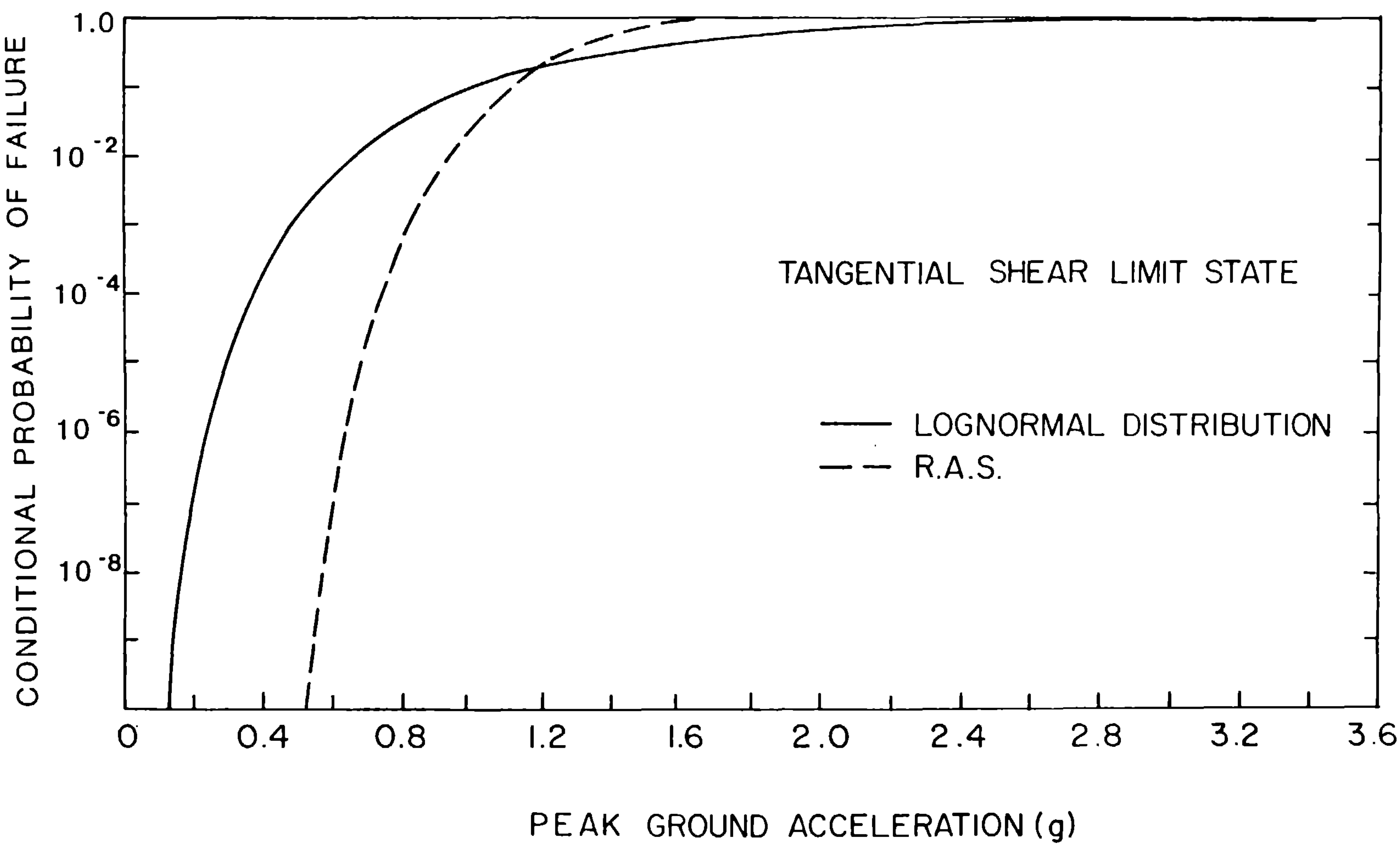


Fig. 4 Comparison of Two Fragility Results

difference is observed in the tail region. Hence, the author believes that it is important to perform a realistic evaluation of component fragility.

Response Analysis

In the current fragility evaluation methods, the treatment of response analysis vary from almost no analysis to detailed finite element analyses. It is often heard that there are thousands of components in a nuclear power plant and thus, detailed response analyses are prohibitively expensive. On the other hand, in view of the delicate nature of fragility evaluation, a certain degree of response analysis is necessary in order to realistically evaluate the component fragility. Taking both viewpoints into consideration, a simplified response analysis method seems appropriate for the purpose of fragility evaluation. This simplified method should be based on a relatively simple model which captures the major features of component behavior, such as non-linear characteristics, and should use less cumbersome analytical schemes to predict its responses to earthquakes.

SECTION 4
SEISMIC MARGINS ASSESSMENT

In recent years, advances in seismology have led to the perception that the potential earthquake in the Eastern United States may be higher than originally assumed. Hence, there is a need to develop a method to assess the actual seismic capacity of nuclear power plant facilities especially those located in the eastern United States [20]. A seismic PRA study can be utilized to assess the seismic margins. However, the large uncertainties associated with seismic hazard analysis and the subjective input used in the fragility evaluation make the result from seismic PRA less reliable.

Because of the conservatism built in the design process, well-designed nuclear power plant structures and safety-related systems, in general, are capable of withstanding earthquakes larger than the original design basis such as SSE. A general definition of seismic margin is expressed in terms of the earthquake peak ground acceleration that compromises plant safety, specifically leading to melting of the reactor core. The "peak ground acceleration" is defined as the average of the peak values of the two horizontal free-field ground-surface accelerations.

Recently, two major research programs have been undertaken to develop seismic margin review procedures. The first program is funded by the NRC. An expert panel is formed to formulate a methodology and to recommend the review procedures [21,22]. The methodology is currently being applied on a trial basis to estimate the seismic margin of the Maine Yankee Atomic Plant. The second program is funded by the Electric Power Research Institute (EPRI). A modified methodology based on the procedure developed by the NRC expert panel has been developed [23]. The methodology is being applied to estimate the seismic margin of the Catawba Nuclear Power Plant. These two seismic margins approaches have the following characteristics. First, the seismic margins approach does not conduct a probabilistic seismic hazard evaluation. A single reference earthquake which may be called seismic margin earthquake (SME), is selected for the seismic margins review. For example, an earthquake with a PGA=0.3g may be selected as a criterion. Then, the purpose of the seismic margin study is to determine whether the nuclear power plant has the capability to withstand this selected 0.3g earthquake. Second, the seismic margins approach does not require the assessment of a family of fragility curves, which result from the need to explicitly quantify the randomness and uncertainties. A value with a high confidence of a low probability of failure (HCLPF) is used to represent the fragility of structures and equipment. The HCLPF is a conservative representation of capacity and is discussed in the following section. Third, the system analysis is reduced to minimum in the seismic margins review.

4.1 HCLPF Values of Structures and Equipment

The high confidence of low probability of failure (HCLPF) capacity is a conservative representation of capacity. It corresponds to an earthquake level at which it is extremely unlikely that failure will occur. The HCLPF values of structures and equipment may be derived from earthquake or test data and engineering judgement. If the fragility data from seismic PRA are available, the HCLPF value approximately corresponds to a 95 percent confidence that probability of failure will be less than five percent. If the randomness and uncertainty are not separated explicitly, then the author recommends that the HCLPF value may be set to be one percent of the probability of failure estimated from the composite fragility curve. In Ref. 23, Kennedy also suggests a deterministic procedure to calculate HCLPF value.

4.2 NRC-Sponsored Seismic Margin Approach

In mid-1984, the NRC formed an "Expert Panel on Quantification of Seismic Margins" [21]. The expert panel has established an approach for seismic margin reviews for a selected earthquake. The approach utilizes a series of screening procedures [21,24]. The first screening is done on the plant system functions. After reviewing all published seismic PRA's, the expert panel concluded that for PWR plants, only two plant system functions, shutting down the nuclear reaction and early emergency core cooling, need to be reviewed. For all initiating events, fault and event trees pertinent to these two functions are developed. From these trees, the Boolean expressions and minimal cut sets are established.

The second screening is done by sorting the components in the above systems into two classes: those whose HCLPF capacities are generically higher than the review earthquake level and those whose HCLPF capacities cannot be assumed to be higher than the review earthquake level without further examination. The components in the latter group are called "screened-in" components. The generic capacities of components have been established by reviewing the fragility estimates in about 20 seismic PRA's, actual earthquake data, and qualification and test data.

The screening and margin review are aided by performing at least two plant walkdowns. The first plant walkdown is aimed at confirming that no weaknesses exist in the plant structures and equipment that would make their HCLPF capacities lower than the generic values. It is also intended to confirm the accuracy of system descriptions found in plant design documents and to identify any system interactions, system dependencies and plant unique features. The second plant walkdown is meant for collection of specific data (e.g., size and other physical characteristics) of "screened-in"components.

The fragility curves of the "screened-in"components are estimated by the Zion method described in section 3.1. The HCLPF capacity is calculated as the earthquake peak ground acceleration at which there is less than 5 percent probability of failure with 95 percent confidence. The HCLPF capacities of the system and the plant is estimated using the minimal cut sets and the HCLPF values of structures and equipment appearing in those minimal cut sets.

4.3 EPRI-Sponsored Seismic Margin Approach

The Electric Power Research Institute (EPRI) initiated a program in late 1985 to develop a seismic margin review procedure to be used by utilities. Ref. 23 describes the EPRI approach in detail. Herein, the essential concept in EPRI approach is presented.

In plant system aspect, the EPRI program utilizes the concept of success path. A success path is an operational sequence of plant systems that will bring the plant to a stable condition (either hot or cold shutdown) and maintain that condition for at least 72 hours. Several success paths may exist. The idea is to select the success path for which it will be easiest to demonstrate an adequate seismic margin. Only those components in the success path need to be reviewed. The primary benefit of this success path approach is to reduce the amount of system modeling and to reduce the number of components. Furthermore, this approach is purely deterministic. These benefits are gained at the expense of possibly not finding the path with the highest seismic capability.

For those components in the success path, a lower-bound estimate of capacity in terms of peak ground acceleration level is needed. If the SME level is set sufficiently low (such as 0.25g), then it will be possible to eliminate many components from review (subject to a walkdown verification, which is always necessary) on the basis that the review team have high confidence that the capacities of these components exceed the SME level.

For those components for which HCLPF capacity estimates are required, the EPRI approach is to use a set of pre-established conservative deterministic failure margin (CDFM) criteria and procedures to directly compute the HCLPF capability. Details of CDFM criteria are described in Ref. 23. The seismic margin capability (expressed in terms of HCLPF) for any success path is then equal to the HCLPF capability of the weakest component in that success path.

SECTION 5
CONCLUSIONS

This report reviews the seismic probabilistic risk assessment and seismic margins studies for nuclear power plants in the United States. The techniques employed in these studies are briefly described. Seismic PRA is a systematic process to evaluate the safety of nuclear power plants. In the process, it integrated all the elements such as seismic hazard, component fragility and plant system. Thus, it provides the overall view of the safety of an entire plant under a seismic event.

The major tasks of a seismic PRA such as the evaluation of hazard curves, component fragility and plant systems are also present in probabilistic analyses of non-nuclear facilities. The concepts and techniques embodied in seismic PRA for nuclear power plants can be applied to other types of engineering facilities.

In order to reduce the uncertainty in a PRA study, further research in each major areas is needed. At present, NRC and EPRI are funding separately two major research projects for evaluating the seismic hazards in the eastern United States in order to reduce the uncertainties in the seismic hazard analysis [8,9]. In addition, NRC is also sponsoring a component fragility program [25]. Under this program, existing data for equipment will be collected and new tests for fragility data may be performed. However, no research program on structural fragility is being conducted in the U.S.. It is hoped that a research program on structural fragility will be sponsored. Under such a program, identification of failure modes and response analysis need special attention. Failure modes should be clearly defined and the most probable failure mode should be identified so that it can used to estimate the structural capacity. Furthermore, a simplified response analysis method should be employed to realistically predict structural behavior. In this regard, the understanding of non-linear behavior of structures under severe seismic loading and analytical methods (probabilistic and deterministic) to predict non-linear behavior need to be improved. The fragility evaluation is not completed without verification with actual data. At present, structural fragility data are very scarce and obviously it needs to collect all pertinent data that are available.

SECTION 6
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