Chapter 8
Seismic Probabilistic Risk Assessment

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Abstract This chapter presents an overview of the seismic probabilistic risk assessment (PRA) for nuclear power plants. First, the basic concept of seismic PRA and its application to continuous improvement of seismic safety of nuclear power plants are explained. Then, the methodology of seismic PRA for nuclear power plants is explained. Seismic PRA process can be divided into probabilistic seismic hazard analysis, fragility analysis of structures/components, and accident sequence analysis. As for the probabilistic seismic hazard analysis, modeling of earthquake occurrence, a method for earthquake ground motion prediction, and logic tree model are introduced. Then, the fragility analysis of structures/components is described. This includes an explanation of the selection of failure modes, and the realistic strength and realistic response of buildings/components.

Keywords Probabilistic risk assessment · Accident scenario · Fragility analysis · Seismic hazard analysis · Fragility curve · Event tree · Fault tree

8.1 Probabilistic Risk Assessment (PRA)

The accident that took place at the Fukushima Daiichi Nuclear Power Plant as a result of the 2011 Great East Japan earthquake and consequent tsunami raised awareness of the risks associated with nuclear facilities. To achieve high level of safety for nuclear facilities, probabilistic risk assessment is considered useful because it provides insight into the weakness by identifying as many possible accident scenarios as possible.

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Risk is defined as combination of consequence of an accident and its associated likelihood, i.e., occurrence probability.

When a severe accident happens at a nuclear power plant, leading to damage to the reactor core and the reactor containment vessel, large amount of radioactive material are released into the environment, exposing the public in the vicinity of the plant with respect to radiation exposure as well as environmental contamination.

As a result of probabilistic risk assessment, contributors to accident risk can be quantitatively assessed, which are potential causes of an accident. Moreover, PRA can estimate quantitatively the effectiveness of countermeasures to be taken to reduce risks.

Quantitative safety goal and subsidiary objectives, so-called performance goals, are referred to as criteria that represent the societal acceptability of the risks (Appendix 8.1).

Safety goals usually concern the radiation risk of the public as well as environmental contamination, while performance goals concern, for example, equivalent plant condition such as core damage frequency as well as large early release frequency.

8.2 Categorization of Initiating Events

Events that initiate accidents are classified into (a) random failure of components, (b) internal hazards such as internal flooding and an internal fire, and (c) external hazards. External hazards are classified into natural hazards such as earthquakes and tsunamis, and human-induced hazards such as an airplane attack and an intentional act.

8.3 Overview of Seismic PRA

In seismic PRA, attention is focused on earthquakes that may happen in the future and affect the safety of nuclear power plant. The failure probabilities of structures (e.g., buildings) and components are assessed. Uncertainty associated with the earthquake ground motion, the responses of buildings and components, and strength of structures and components are considered. Then, the occurrence probabilities (or frequencies) of various accident sequences and the magnitude of their consequences are estimated.

Furthermore, in seismic PRA, the core damage frequency is estimated on the basis of seismic hazard analysis, structures/components fragility analysis, and accident sequence analysis. The seismic hazard analysis estimates the probability of occurrence, within a certain period of time (e.g., 50 years), of an earthquake for which the ground motion, e.g., at the hypothetical free surface of bedrock, exceeds a certain level. The fragility analysis gives the failure probability of structures/components (for example, buildings, structures, and component piping systems) as a function of the seismic ground motion level. Figure 8.1 illustrates the overview of seismic PRA.
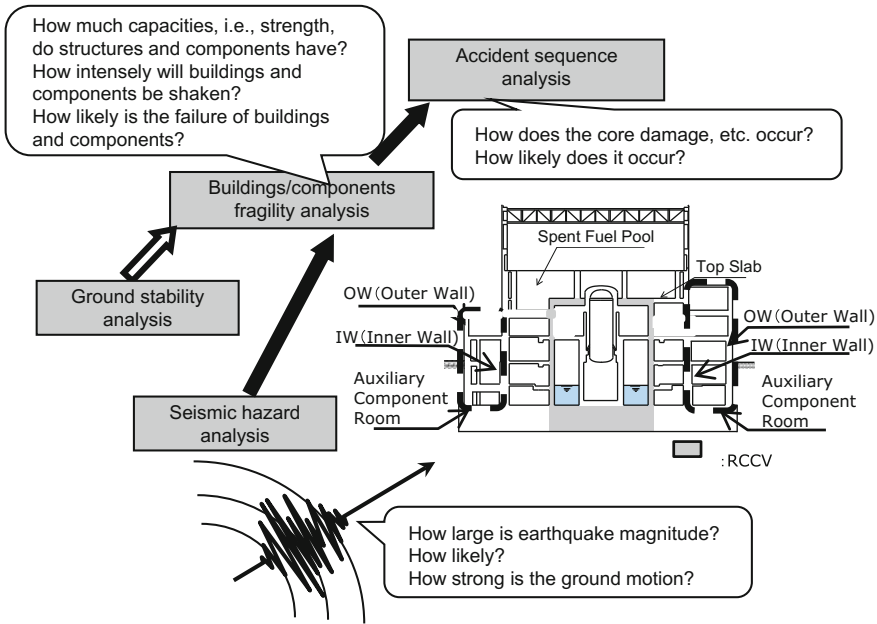
Fig. 8.1 Overview of seismic PRA

Figure 8.2 shows the seismic PRA procedure.

(1) Collection and analysis of site/plant information, and field surveys

To start with, the information required for seismic PRA is collected and compiled. Field surveys (site/plant walkdown surveys) are performed as required. Through field surveys, the type of information is obtained which cannot be acquired sufficiently from documents alone. They may include the information whether components and piping systems have been installed exactly as designed, the presence of any facility that may affect another facility, and factors that may complicate post-earthquake recovery actions.

(2) Identification of accident scenarios

According to plant information and field survey results obtained in Step (1), possible scenarios of an accident, for example, leading to core damage, are identified.

(3) Seismic hazard analysis

Based on information on the seismic source locations and magnitudes, occurrence frequencies of earthquakes that may affect the nuclear power plant, the probability of ground motion, e.g., at virtually free surface of bedrock, exceeding a certain level are estimated.

(4) Ground stability analysis

The potential effects of hazards such as sliding of foundation ground under the buildings/structures and slope failure are studied. Their potential impacts on structures and components require attention.
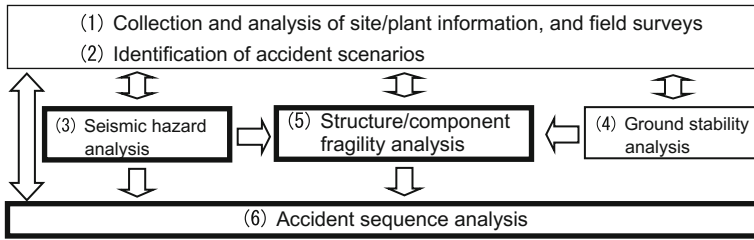
（1）Collection and analysis of site/plant information, and field surveys
（2）Identification of accident scenarios

| （3）Seismic hazard analysis | （5）Structure/component fragility analysis | （4）Ground stability analysis |

（6）Accident sequence analysis

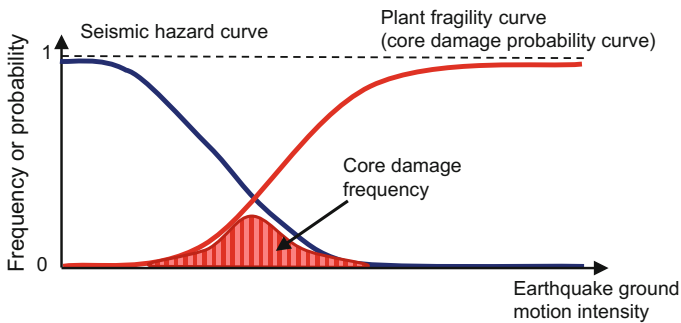**Fig. 8.2** Seismic PRA procedure

Fig. 8.3 The core damage frequency obtained from the seismic hazard curve and the plant fragility curve

(5) Structure/component fragility analysis

On the basis of information on the dynamic response analysis and strength of structures/components, failure probabilities are estimated as a function of the earthquake ground motion intensity. The failure should not be assessed based on conservative design assumptions, but based on realistic response as well as realistic strength of structures/components.

(6) Accident sequence analysis

On the basis of the seismic hazard analysis, the fragility analysis and information about random failures of safety functions and the scenarios of accidents leading to core damage are analyzed (in the form of event trees and fault trees). The conditional probability and occurrence frequency of core damage are calculated. This leads to the identification of components and facilities that are likely to serve as a cause of core damage.

Figure 8.3 shows how the core damage frequency is calculated from the seismic hazard curve and the plant fragility curve (representing conditional probabilities of core damage as a function of earthquake ground motion intensity).

8.4   Probabilistic Seismic Hazard Analysis

A relationship between the earthquake ground motion intensity and its likelihood of occurrence is obtained by the probabilistic seismic hazard analysis (PSHA). This section describes the conventional method of PSHA for a nuclear facility.

8.4.1   Probabilistic Seismic Hazard Analysis Flow

As shown in Fig. 8.4, a seismic hazard curve, a relationship between the earthquake ground motion intensity and its annual exceedance frequency, is obtained by taking account of various uncertainties. The uncertainties are due to the location and characteristics of seismic sources, and the characteristics of the seismic wave propagation and ground motion amplification. Typically, amplification up to reference bedrock surface (virtually free surface of bedrock) is considered in seismic hazard analysis. Amplification from reference rock to surface ground is considered in fragility analysis.

Figure 8.5 shows the seismic hazard analysis flow.

(1) Identification of the seismic source model
    In seismic hazard analysis, a probabilistic model is employed to model the possibilities of earthquake occurrence that may affect the target site. The magnitudes and occurrence of such earthquakes are considered probabilistically and statistically.
(2) Ground motion prediction model
    A ground motion prediction model, i.e., attenuation formula, is used to estimate the probability distribution of earthquake ground motion at the target site for each seismic source identified in Step (1).

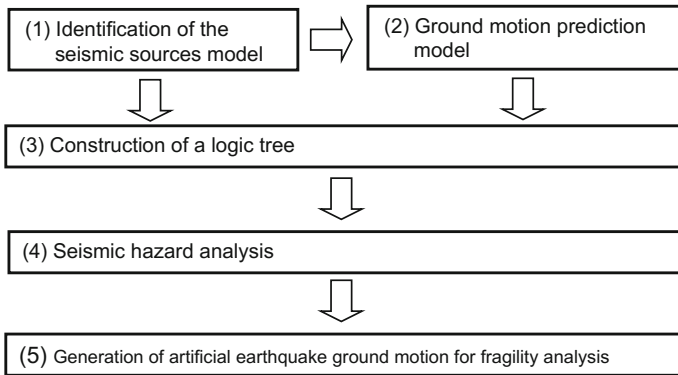**Fig. 8.4** Probabilistic seismic hazard curve
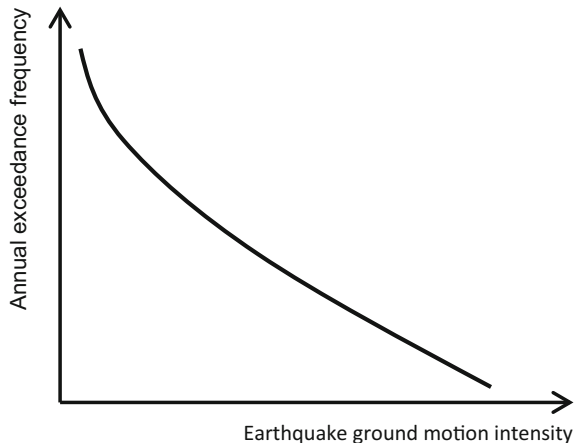
Fig. 8.5 Seismic hazard analysis flow

(3) Construction of a logic tree

For the source model and ground motion prediction model, a logic tree is employed to account for epistemic uncertainty, i.e., knowledge-oriented uncertainty, in parameters that differ in assumptions concerning, for example, the fault length and the earthquake magnitude.

(4) Seismic hazard analysis

As a result of analysis, the seismic hazard curve, i.e., the relationship between the earthquake ground motion intensity and the annual exceedance frequency, is obtained. Uncertainties in the estimated hazard curve are analyzed using the logic tree.

(5) Generation of artificial earthquake ground motion for fragility analysis

A seismic hazard curve is calculated for response spectra of the ground motion for different vibration periods. A value representing a specified level of exceedance probability is selected at each vibration period for the response spectrum. Then, a uniform hazard spectrum is obtained by connecting these points. From the uniform hazard spectrum, simulated ground motion for use in dynamic response analysis is generated.

8.4.2 Probabilistic Seismic Hazard Analysis Method

8.4.2.1 Seismic Source Model

Considering all earthquakes that may affect the target site, seismic sources are modeled and the occurrence probabilities of such earthquakes are estimated. Usually, the potential seismic sources within a distance of approximately 100–150 km from the target site are considered for seismic hazard analysis.

Earthquakes of all seismogenic mechanisms, including inland crustal earthquakes, interplate earthquakes, and intra-oceanic plate earthquakes, should be addressed.
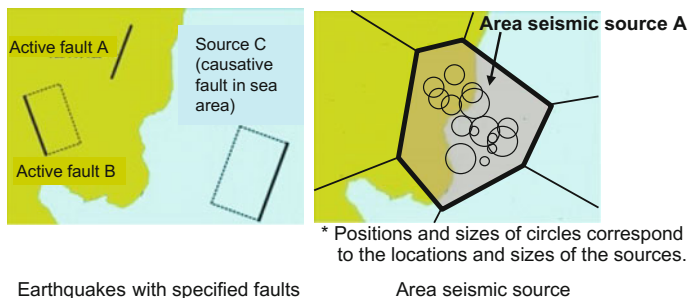
Fig. 8.6 Earthquakes with specified faults and area seismic sources

As shown in Fig. 8.6, the seismic sources are classified into two categories: earthquakes with specified faults, for which the magnitude and location can be specified in advance, and area seismic sources (i.e., earthquakes without specified faults or diffuse seismicity), where seismic activities of unspecifiable magnitudes at unspecifiable locations within a certain zone are modeled statistically.

An example of interplate earthquakes is earthquakes that are located off the Pacific coast of Tokai/Tonankai/Nankai area in Japan. The Japanese Government's Headquarters of Earthquake Research Promotion has released estimation about the probabilities of their occurrence in the regions as shown in Fig. 8.7.

The probability of occurrence of a particular type of earthquake is modeled using a time-dependent probability model to address the periodicity of earthquake occurrence, if the time and the frequency of past occurrences are known. In the case that the time of past occurrences is unknown, a homogeneous probability model such as a Poisson model is used alternatively. A homogeneous probability model assumes an unchanging probability of occurrence in time. Figure 8.8 shows three options (a–c) to estimate annual occurrence frequency or probability of earthquake.

As for the types of earthquakes that are difficult to be specified in advance in terms of magnitude, location, and their occurrence, the occurrence frequencies are modeled using the Gutenberg–Richter law as shown in Fig. 8.9. The spatial distribution of earthquakes is assumed to be uniform within the same seismotectonic zone. A seismotectonic zonation proposed for Japan is shown in Fig. 8.10.

8.4.2.2 Ground Motion Prediction Model

Earthquake ground motion is estimated using a ground motion prediction equation, i.e., attenuation formula. Attenuation formula is usually a function of the magnitudes and fault-to-site distance and site amplification characteristics. The predicted earthquake ground motion is an average value. Attenuation formula is derived by means of regression analysis from ground motion records at many observation stations, and usually exhibits large variability. Referring both to the average value and the variability, the probability of ground motion exceeding a certain level is
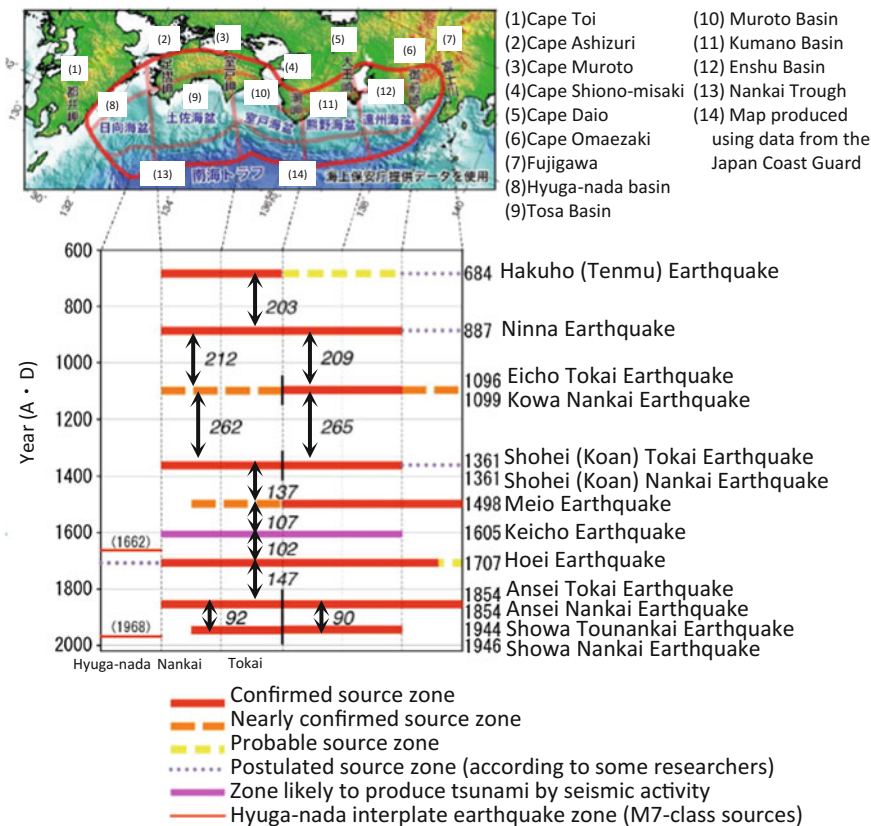
(1)Cape Toi
(2)Cape Ashizuri
(3)Cape Muroto
(4)Cape Shiono-misaki
(5)Cape Daio
(6)Cape Omaezaki
(7)Fujigawa
(8)Hyuga-nada basin
(9)Tosa Basin

(10) Muroto Basin
(11) Kumano Basin
(12) Enshu Basin
(13) Nankai Trough
(14) Map produced
     using data from the
     Japan Coast Guard

684 Hakuho (Tenmu) Earthquake
887 Ninna Earthquake
1096 Eicho Tokai Earthquake
1099 Kowa Nankai Earthquake
1361 Shohei (Koan) Tokai Earthquake
1361 Shohei (Koan) Nankai Earthquake
1498 Meio Earthquake
1605 Keicho Earthquake
1707 Hoei Earthquake
1854 Ansei Tokai Earthquake
1854 Ansei Nankai Earthquake
1944 Showa Tounankai Earthquake
1946 Showa Nankai Earthquake

━━━ Confirmed source zone
━ ━ Nearly confirmed source zone
━ ━ Probable source zone
······· Postulated source zone (according to some researchers)
━━━ Zone likely to produce tsunami by seismic activity
─── Hyuga-nada interplate earthquake zone (M7-class sources)

Fig. 8.7 Temporal–spatial distributions of earthquakes occurrence around the Nankai Trough [1]
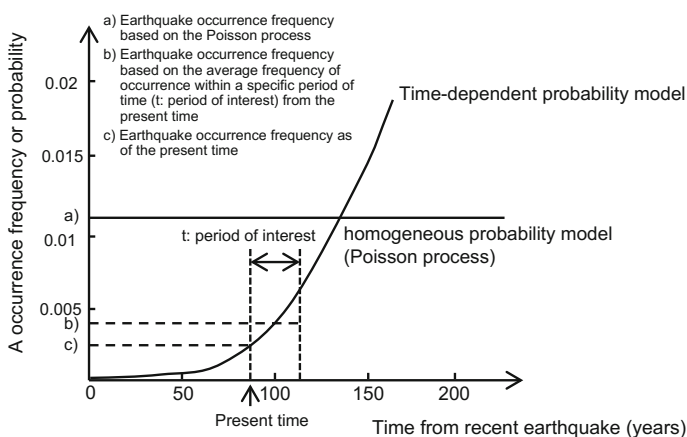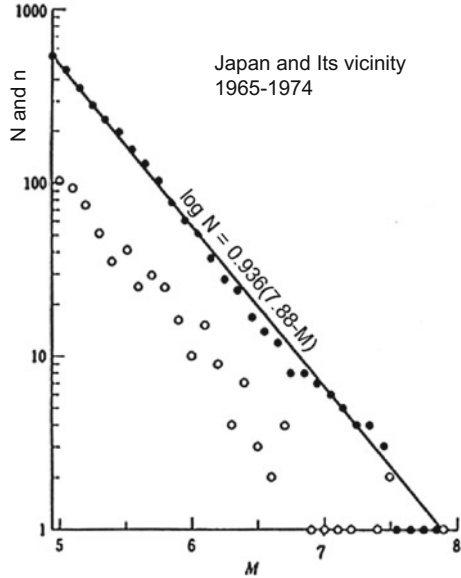

Fig. 8.8 Three options to obtain earthquake occurrence frequency

Fig. 8.9 Gutenberg–Richter law [2]. *White dots* correspond to n(M) which is the number of earthquakes in which the magnitude is *M*. *Black dots* represent N (M) which is the total number of earthquakes in which the magnitude is *M* or above

estimated. As shown in Fig. 8.11, the variability of attenuation formula, i.e., the variability of logarithm of the ground motion, is modeled as the normal distribution.

8.4.2.3 Logic Tree

Uncertainty in assumptions concerning the parameters is called epistemic uncertainty. In seismic hazard analysis, the epistemic uncertainty in parameters, e.g., the fault length, earthquake magnitudes, and earthquake occurrence frequency, is modeled as possible different opinions among experts. Therefore, a logic tree, like the one shown in Fig. 8.12, is constructed to account for all possible opinions. The logic tree is a tree diagram showing differences in expert opinions. With the weighing by confidence in different opinions, it contributes to the estimation of uncertainty in seismic hazard analysis.

8.4.2.4 Seismic Hazard Curve

As shown in Fig. 8.13, the seismic hazard curves for individual sources are unified to produce a seismic hazard curve. The result of seismic hazard analysis may change in the future as more seismological knowledge are accumulated. It is advisable to examine the validity of seismic hazard analysis from time to time for continuous updating.
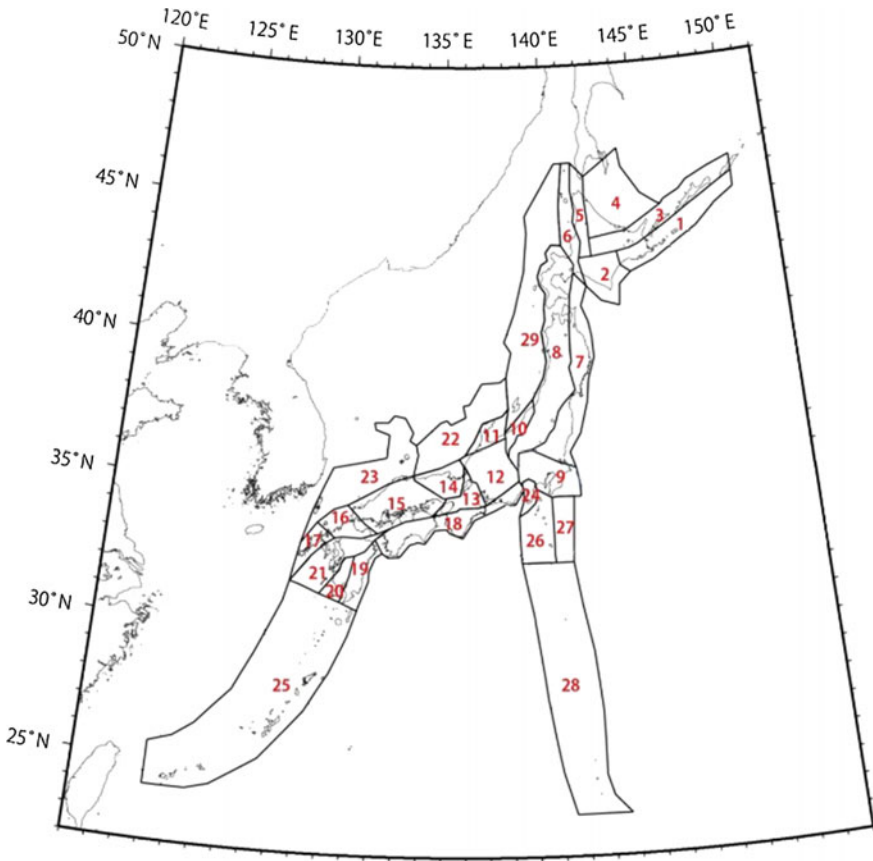
Fig. 8.10 Seismotectonic zonation for earthquake without specified faults [2]

8.4.2.5 Generation of Artificial Earthquake Ground Motion for Fragility Analysis

A seismic hazard curve is produced for acceleration response spectrum, i.e., the maximum responses to the ground motion of one-mass-spring-damper system (Part II, Chap. 14, Sect. 14.1) with different natural vibration periods. For the same exceedance frequency, the response values are plotted at each vibration period to produce a uniform hazard spectrum as shown in Fig. 8.14. The fragility analysis is performed using the artificial time history earthquake ground motion generated so that its response spectrum fits the uniform hazard spectrum.
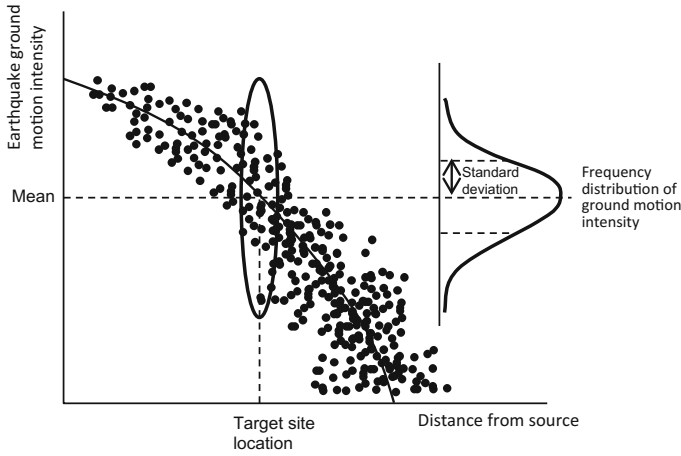
Fig. 8.11 Mean and variability of ground motion estimated using the attenuation formula
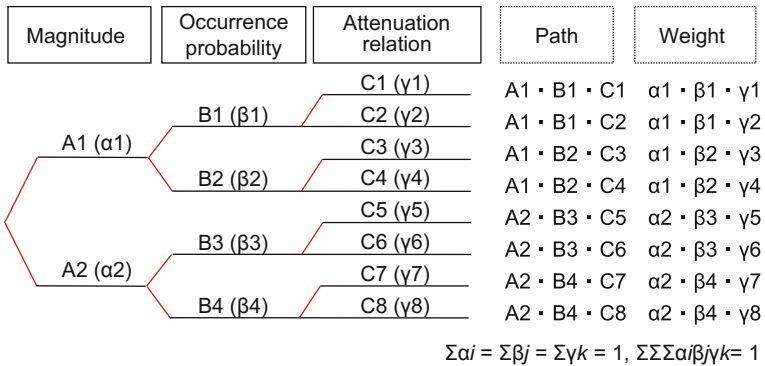

Fig. 8.12 An example of a logic tree

8.5   Structure/Component Fragility Analysis

Relationships between the earthquake ground motion intensity and probability of failure of structure/component are obtained by the seismic fragility analysis. This section describes the conventional method of the seismic fragility analysis.

8.5.1   Fragility Analysis Flow

A fragility curve shows conditional failure probabilities for different ground motion intensity levels. On the basis of information concerning the dynamic response and strength of structures and components, a fragility curve is developed. A fragility
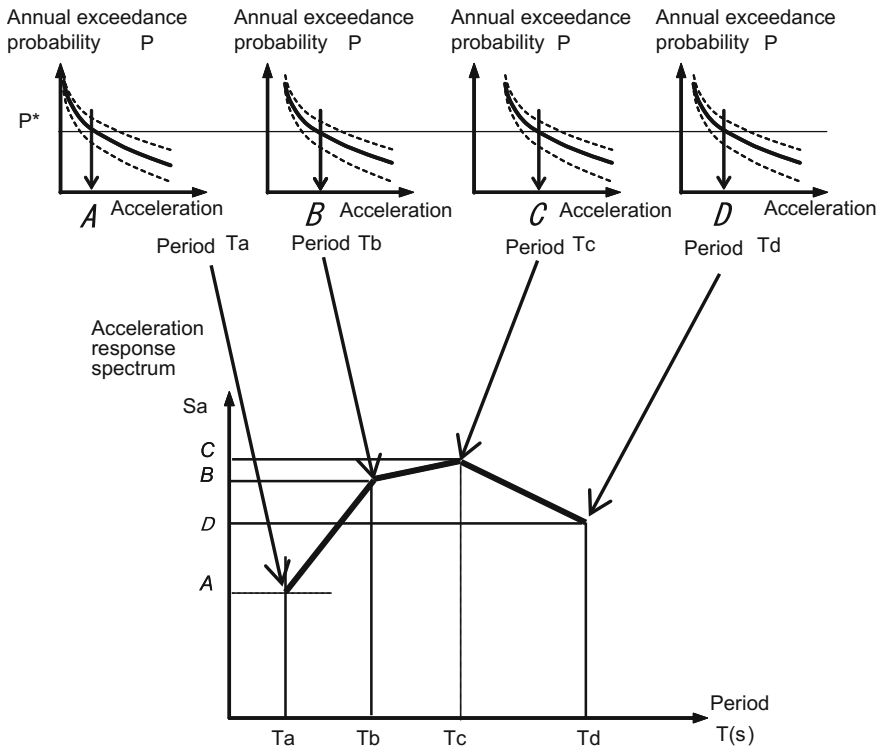
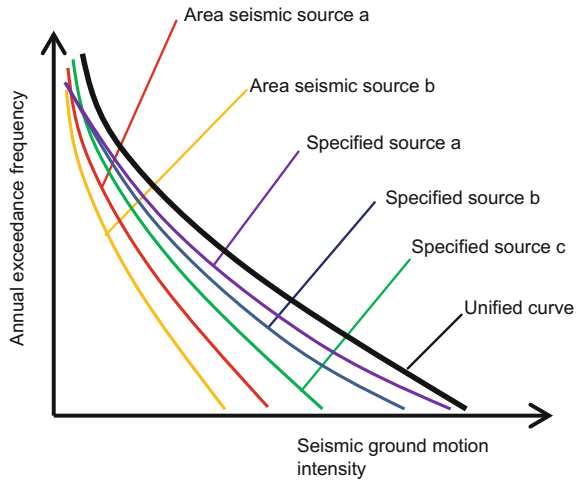Fig. 8.13 Seismic hazard curve
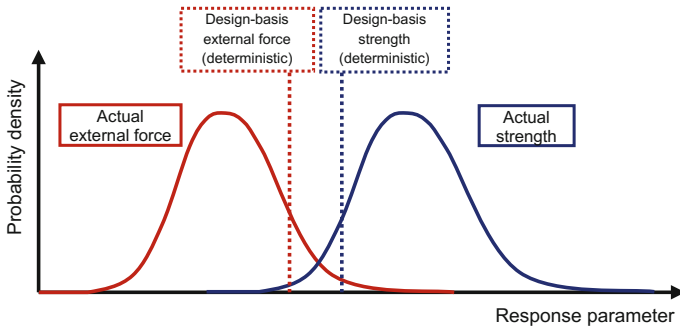

Fig. 8.14 Uniform hazard spectrum

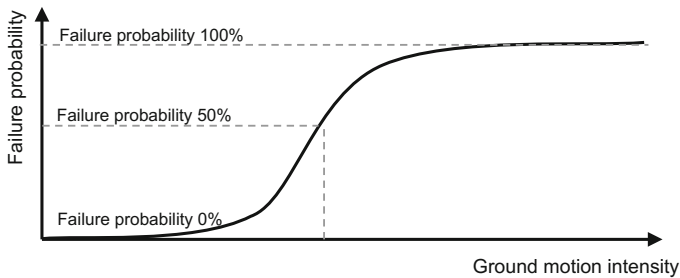**Fig. 8.15** External force and strength relationship

Fig. 8.16 Fragility curve

curve is estimated for structures and components that are significant in assessing the nuclear power plant risks.

For earthquake-resistant design, a deterministic approach is employed and structural components are designed to have an enough safety margin for the deformation and stress produced by the design basis external forces. On the other hand, the actual external forces from an earthquake and the actual material strength inherently exhibit scatter. In other words, the external forces and the strength of structures and components are random variables as shown in Fig. 8.15, and the failure probability of structures and components is represented by a fragility curve like the one shown in Fig. 8.16.

Figure 8.17 shows the structures/components fragility analysis flow.

(1) Selection of target structures and components, and the determination of their failure modes
    After selecting target structures and components, their failure and associated response parameters to be used for determining their failure are defined.
(2) Selection of an analysis method
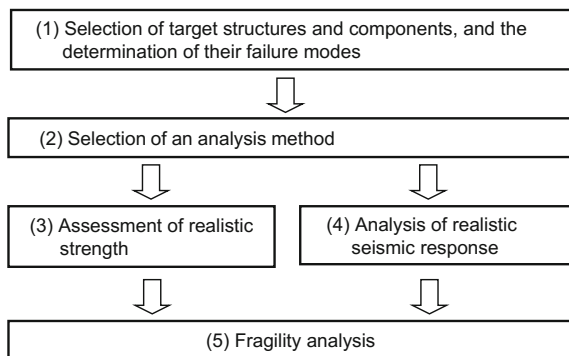   The analysis method is chosen in view of required accuracy and the objectives of the analysis.

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┌─────────────────────────────────────────────────────┐
│ (1) Selection of target structures and components, and the │
│         determination of their failure modes              │
└─────────────────────────────────────────────────────┘
                          ⬇
┌─────────────────────────────────────────────────────┐
│ (2) Selection of an analysis method                      │
└─────────────────────────────────────────────────────┘
              ⬇                           ⬇
┌────────────────────────┐   ┌────────────────────────┐
│ (3) Assessment of realistic │   │ (4) Analysis of realistic   │
│          strength          │   │       seismic response      │
└────────────────────────┘   └────────────────────────┘
              ⬇                           ⬇
┌─────────────────────────────────────────────────────┐
│              (5) Fragility analysis                      │
└─────────────────────────────────────────────────────┘
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Fig. 8.17 Structure/component fragility analysis flow

(3) Assessment of realistic strength

For each of the target structures and components, the limit beyond which it will fail (i.e., the strength of the structures or components) is assessed probabilistically. The assessment method that may be employed is either an empirical method using experiments, a numerical method based on analysis, or a method that makes use of engineering judgments integrating both empirical and numerical methods.

(4) Analysis of realistic seismic response

For each of the target structures and components, the dynamic response is estimated stochastically, i.e., as a random variable. Conventionally, the input ground motion for this analysis is that derived from the uniform hazard spectrum (Sect. 8.4.2).

(5) Fragility analysis

On the basis of the result of the assessment of the probabilistically estimated strength and response, the fragility curves for the structures and components are obtained.

8.5.2 Building Fragility Analysis

8.5.2.1 Selection of the Failure Mode

First, the building's failure mode and the elements of the building prone to failure are determined. This is followed by the selection of response parameters for assessment of failure and the ground motion intensity.

Failure modes of structure that may lead to the damage of buildings may include sliding, overturning, story collapse, failure of local elements, and the failure of nonstructural members like partitions, ceilings, and doors. The dominant failure mode is selected from among them, and the safety critical elements of the building are identified. Conventionally, a failure mode like story collapse may be assumed to lead directly to core damage.

8.5.2.2   Selection of the Response Parameter

A parameter of the seismic response (e.g., stress, acceleration, strain, or deformation) is chosen for assessment of failure. Note that a failure is assessed probabilistically for the chosen response parameter.

When assessing the probability of shear failure of seismic walls leading to story collapse, the shearing force or shearing strain is chosen as the response parameter.

8.5.2.3   Assessment of Realistic Strength

A typical process of earthquake-resistant design includes the calculation of the dynamic response of building to design input earthquake ground motion. This process is to verify that the dynamic response does not exceed the allowable limit (design strength) depending on the material property. A fragility curve is derived considering the probability distribution of the realistic dynamic response and the probability distribution of realistic strength.

The probability distribution of strength is obtained by statistically analyzed experimental data. The dominant failure mode of buildings considered for a reactor building is the shear failure of a seismic wall made of reinforced concrete.

Table 8.1 summarizes failure limit values of shearing stress and shearing strain of reinforced concrete seismic wall. Figure 8.18 shows the relationship between the shear stress and the shear strain of seismic wall. The failure limit point for seismic walls is probabilistically determined on the basis of high confidence value for experimental results. However, such values may change in the future as more data are collected in experiments. It is advisable to examine the validity of experimental data from time to time and to update the failure limit point values.

8.5.2.4   Analysis of a Realistic Seismic Response

The dynamic response analysis is conducted probabilistically in consideration of uncertainty in the input earthquake ground motion and material property values.

In the analysis of the realistic seismic response, the factors that may significantly affect the response must be accounted for by considering the causes of the

Table 8.1 Shearing stress and strain settings [3]

Failure limit point (assessment index)		Mean	Coefficient of variation (including both aleatory and epistemic uncertainties)
Shearing stress τ_u		Strength equation	0.15
Shearing strain γ_u	Box wall	5.36×10^{-3}	0.24
	Ring wall	9.77×10^{-3}	0.33

Fig. 8.18 Shearing stress and shearing strain relationship of seismic wall (conceptual)
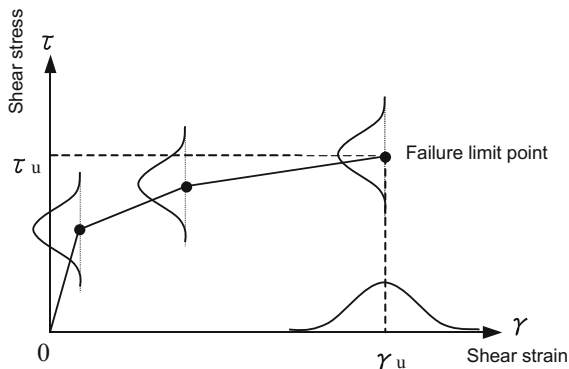
Table 8.2 Characteristics of different sampling methods [3]

Method	Strength	Weakness
First-order second-moment method	– Simple and highly applicable – Sensitivity of input parameter can be estimated	– Limited applicability – Estimation at the tail of probability distribution is relatively inaccurate because the method focuses on values close to the mean value
Multiple point estimate (two-point estimate, etc.)	– Simple and highly applicable	– Requires assumption about probability distribution – The number of trial increases with the number of input parameters – Includes certain errors
Monte Carlo method	– Very highly applicable – The detail including probability distribution can be estimated	– Large number of trial is required in order to achieve accuracy of a satisfactory level
Experimental design method (Latin hypercube method, orthogonal array method, etc.)	– Highly applicable – Sensitivity to input parameter can be estimated – Possible to decrease the number of trial for the Monte Carlo method, two-point estimate, etc.	– Significant errors may arise when there exists a strong nonlinear relationship between input and output

uncertainties. The probability distribution of the dynamic response can be obtained efficiently by means of sampling performed using, for example, the Monte Carlo simulation or the two-point estimate. Table 8.2 summarizes the characteristics of different sampling methods.

In addition, it should be noted that there are two methods for the evaluation of realistic seismic response: a method based on response analysis and a method based

on the response factors (i.e., an assessment of the probabilistic dynamic response using the response factors).

8.5.2.5 Determination of the Fragility Curve

Figure 8.19 shows how the failure probability $F(\alpha)$ for ground motion level α is calculated. As shown in the equation below, $F(\alpha)$ is a conditional probability that $f_R(\alpha, x)$, the probability density function of response to a ground motion intensity level α, exceeds $f_S(x)$, the probability density function of realistic strength. $F(\alpha)$ is calculated as follows:

$$F(\alpha) = \int_0^\infty f_S(x_R) \left(\int_{x_R}^\infty f_R(\alpha, x) \mathrm{d}x \right) \mathrm{d}x_R = \int_0^\infty f_R(\alpha, x_R) \left(\int_0^{x_R} f_s(x) \mathrm{d}x \right) \mathrm{d}x_R \quad (8.1)$$

The large computation time is required when calculation of Eq. (8.1) is done for large number of ground motion level α. Therefore, as shown in Fig. 8.20, discretization is made appropriately and the fragility curve is obtained by interpolation. Typically, the lognormal distribution is assumed for the fragility curve.

8.5.3 Components Fragility Analysis

The fragility of plant components is assessed in consideration of their required functions, paying attention to both structural failures and functional failures.

When assessing the fragility of passive, i.e., static, components such as a tank or heat exchange, the probability of losing required functions due to structural failure in the form of, for example, ductile fracture or brittle fracture is examined. As for active components such as an electrical board, pump, or valve, attention is given not
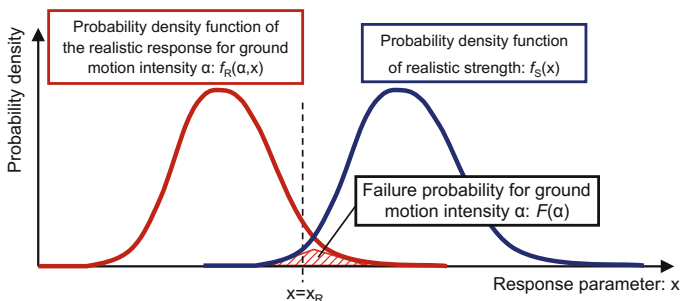

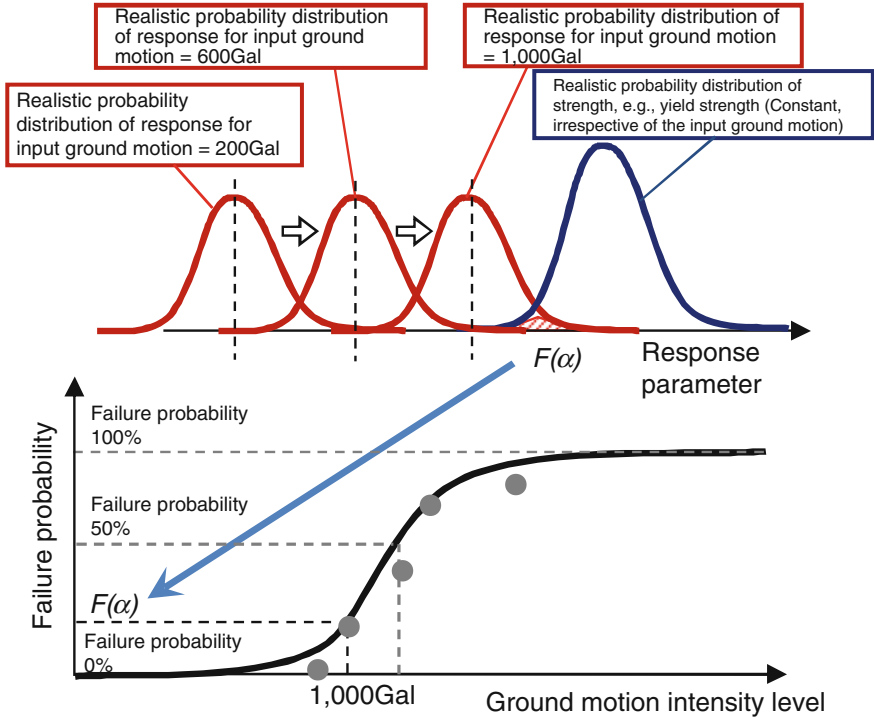**Fig. 8.19** Calculation of failure probability for ground motion intensity α

Fig. 8.20 Interpolation of $F(\alpha)$ to obtain fragility curve

only to the possibility of their structural failure, but also to the possibility of their limit for active or electrical functioning being lost.

To identify the functioning limit for active components, vibration testing is performed using a shaking table as described in Chap. 5, Sect. 5.6.

Table 8.3 summarizes component strength assessment methods. Figure 8.21 shows photos from the vibrating testing of active components.

A component fragility analysis is conventionally performed using the safety factor method. With the safety factor method, fragility is determined by referring to the result of response analysis along with the strength factors and response factors.

The fragility in relation to structural failure is determined in reference to material strength. The fragility in relation to functional failure is determined in reference to vibration test results. The median and uncertainty, i.e., logarithmic standard deviation, are estimated to obtain fragility curve.

The value of the response factor is determined from response analysis, accounting for building-related and component-related uncertainties.

Major assumptions (regarding, for example, uncertainty and the response factor) made in fragility analysis are as follows.

Table 8.3 Component strength assessment [4]

Strength assessment	Target components	Assessment procedure and its characteristics
Strength in relation to structural failure mode	Passive (Static) components: – Tanks – Piping, etc.	– The component strength is assessed on the basis of outputs from the seismic design process – The strength normally varies from plant to plant due to dependency on component geometry (support positions, routing, etc.)
Strength in relation to functional failure mode	Active components: – Pumps – Electrical boards, etc.	– The capability to withstand earthquake and remain functional is assessed by the vibration testing of the given component on a shaking table – The capability of a dynamic component to withstand earthquake and remain functional is normally component-specific

The fragility of a component is measured according to the maximum ground acceleration that the component may tolerate without failing. This maximum tolerable ground acceleration (referred to as the fragility acceleration) is given as a random variable as the following equation

$$A = A_{\mathrm{m}} \cdot \varepsilon_R \cdot \varepsilon_U. \tag{8.2}$$

A_m Median of A, which is the ground acceleration beyond which the component will fail (i.e., median fragility acceleration).

ε_R Random variable, i.e., variable with probability distribution, representing scatter caused by aleatory uncertainty inherent to physical randomness; the mean value is 1.0 while the logarithmic standard deviation is denoted as β_R.

ε_U Random variable representing scatter caused produced by epistemic uncertainty; the mean value is 1.0 while the logarithmic standard deviation is denoted as β_U.

A fragility curve, used for the representing component fragility, is obtained as a cumulative distribution function of the fragility acceleration A.

Figure 8.22 shows examples of three fragility curves with 5, 50, and 95 % confidence level. In the figure, β_R is represented as the gradient of the fragility curve, while β_U contributes to the width between fragility curves of different confidence levels. The fragility curve considering both aleatory and epistemic uncertainties, so-called composite fragility curve, is also shown in Fig. 8.22.

Typically, the component strength can be represented according to the high confidence and low probability of failure (HCLPF) value derived from the fragility curve and then compared with the design basis ground motion. The HCLPF value is the strength at which failure probability of 5 % can be assured with 95 % confidence level.

Fig. 8.21 Photos from the
vibration testing of active
components [4]

Transverse-type pump
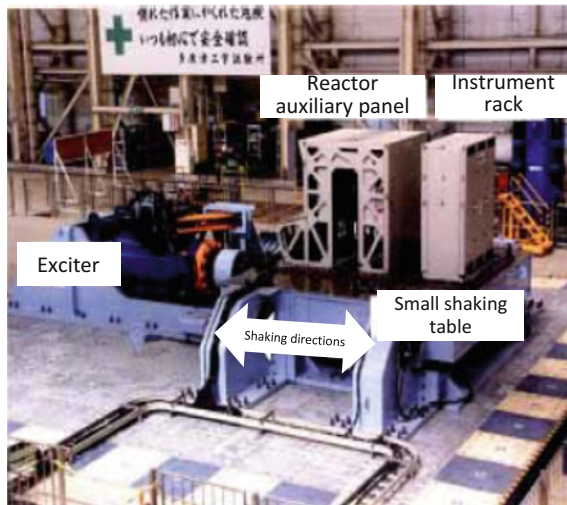
Electrical board

8.6 Accident Sequence Analysis

8.6.1 Accident Sequence Analysis Flow

On the basis of the seismic hazard analysis and buildings/components fragility
analysis, the probability of failure is determined for different facilities to enable the
modeling of accident sequences leading to core damage. The accident sequence
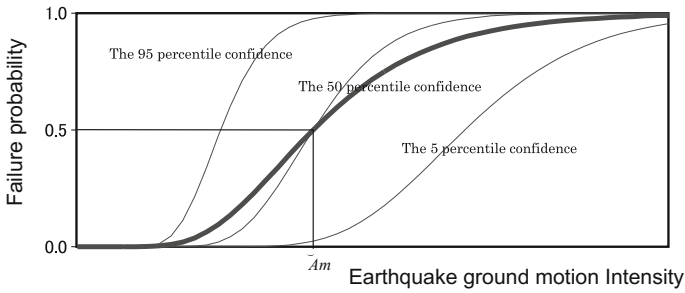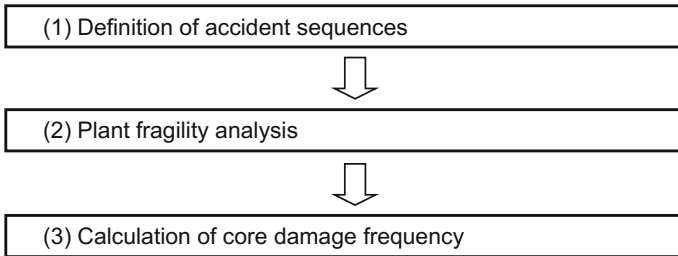
Fig. 8.22 Fragility curve

Fig. 8.23 Accident sequence analysis flow

analysis starts with the analysis of accident scenarios and to calculate core damage frequency. Figure 8.23 shows the accident sequence analysis flow.

(1) Definition of accident sequences
   Accident sequences are defined using event trees and fault trees as a systematic representation of scenarios leading to core damage. The event tree shows how progressive failures of safety functions may lead to an accident including core damage, while the fault tree shows how the combinations of component failures may be a cause of a safety function failure.
(2) Plant fragility analysis
   On the basis of the structure/component fragility analysis and the accident sequence analysis, the fragility of the entire plant is obtained.
(3) Calculation of core damage frequency
   The core damage frequency is calculated according to the seismic hazard analysis and the plant fragility analysis. This is followed by the identification of the dominant accident sequences leading to core damage, and the components and facilities for which failure would contribute significantly to core damage are also identified.

8.6.2   Accident Sequence Analysis Method

Figure 8.24 shows the technical components of accident sequence analysis. Examples of the initiating events for an accident are the loss of off-site power, damage to buildings and structures (including the fracture of the reactor pressure vessel and/or the containment vessel), and piping fracture. After defining how the accident sequences progress depending on the success and failure of maintaining safety functions after the occurrence of the initiating event, the total core damage frequency is calculated as the sum of the probabilities of different accident sequences that lead to core damage.

Following the calculation of core damage frequency, a cut-set analysis is performed to identify the dominant sequences leading to core damage and to identify the components and facilities for which failure contributes significantly to core damage. On the basis of the results of such analyses, introduction of measures for safety improvement (including management-oriented measures) can be decided for the reduction of the core damage frequency.

Seismic Level-2 and Level-3 PRA (Appendices 8.2 and 8.3) are considered to be a future challenge, and researches and development are being conducted toward their realization. Other important challenges include the assessment of risks due to earthquakes combined with other hazards (e.g., tsunamis, floods, and fires) and earthquake risks at multiple-unit plants and multiple sites.
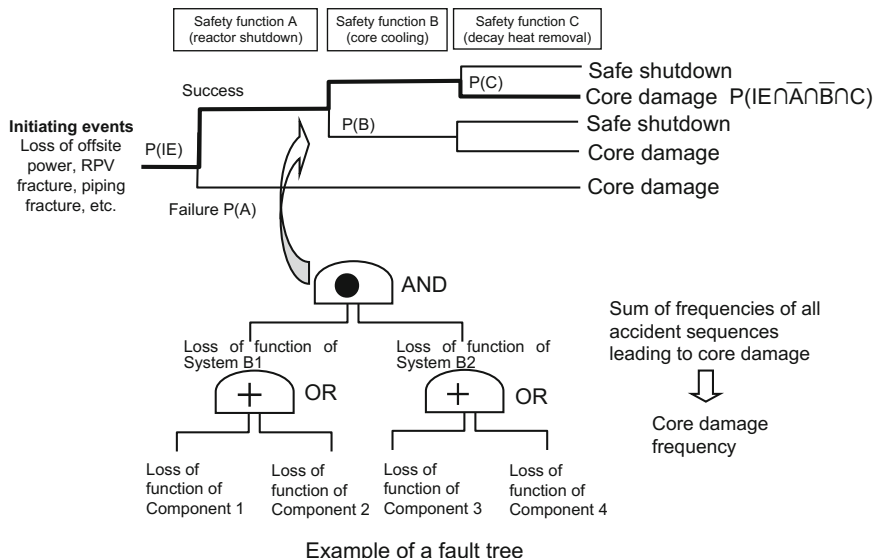

Fig. 8.24 Technical components of accident sequence analysis

Appendix 8.1: Safety Goals of Countries/Agencies Around the World

See Table 8.4.

Appendix 8.2: Levels of Probabilistic Risk Assessment (PRA)

PRA is a method for analyzing and assessing events (i.e., accidents and failures) that can happen for components and systems at a plant in a comprehensive and systematic manner, and it enables the quantitative assessment of the probability of occurrence of each event as well as the magnitude of consequence for each event.

PRA estimates three levels of risk, depending on different stages in accident progression.

Level-1 PRA develops events up to the occurrence of core damage and the core damage frequency is estimated.

Level-2 PRA further develops events leading to a release of radioactive material, and the frequency of occurrence of such release is obtained. PRA up to the assessment of the risk of containment failure is referred to as Level 1.5 PRA.

Level-3 PRA consists of assessing the societal risk including the health risks to the public in the nearby area including its occurrence frequency based on the results of Level-2 PRA.

Figures 8.25 and 8.26 show overview of Level-1, Level-2, and Level-3 PRA.

A methodology for seismic Levels-2 and Level-3 PRA are considered to be a future challenge to be developed.

Appendix 8.3: Overview of Level-2 PRA for Earthquake-Initiated Events

Seismic Level-2 PRA requires the quantification of accident leading to release of radioactive materials including occurrence frequencies and the determination of the source term. But it is basically considered that seismic Level-2 PRA can be implemented by applying Level-2 PRA procedures that address internal events.

Seismic Level-2 PRA identifies and estimates accident scenarios leading to release of radioactive materials. Attention is given not only to the possibility of damage of containment vessel by the earthquake, but also to possible damage of SSCs which support the capacity of the containment vessel. The accident scenarios leading to core damage are classified into several groups according to their types. When classifying, attention is given to the particularities of and similarities among different scenarios. Then, for each group of accident sequences, representative plant

Table 8.4 Safety goals of countries/agencies around the world

Country/agency	Safety goal	Performance goals
IAEA INSAG12 [5]	*General nuclear safety objective* • "To protect individuals, society and the environment by establishing and maintaining in nuclear power plants an effective defense against radiological hazard" *Radiation protection objective* • "To ensure in normal operation that radiation exposure within the plant and due to any release of radioactive material from the plant is as low as reasonably achievable, economic and social factors being taken into account, and below prescribed limits", and to ensure mitigation of the extent of radiation exposure due to accidents" *Technical safety objective* • "To prevent with high confidence accidents in nuclear plants" • "To ensure that, for all accidents taken into account in the design of the plant, even those of very low probability, radiological consequences, if any, would be minor" • "To ensure that the likelihood of severe accidents with serious radiological consequences is extremely small"	Existing plants core damage frequency $<10^{-4}$/plant operating year Future plants core damage frequency $<10^{-5}$/plant operating year Practical elimination of large early releases Severe accident management and mitigation measures could reduce by a factor of at least ten the probability of large off-site releases requiring short term off-site response
United States NRC [6, 7]	*Qualitative safety goals* • Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health • Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks *Quantitative safety goal*	Core damage frequency (existing plant, New plant) $<10^{-4}$/reactor year Large early release frequency (Existing plant) $<10^{-5}$/reactor year Large release frequency (new plant) $<10^{-6}$/reactor year

Table 8.4 (continued)

Country/agency	Safety goal	Performance goals
	• The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed 0.1 % of the sum of prompt fatalities risks resulting from other accidents to which members of the US population are exposed • The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed 0.1 % of the sum of cancer fatality risks resulting from all other causes	

INSAG The International Nuclear Safety Advisory Group
NRC Nuclear Regulatory Commission

The occurrence of severe accident
(Core Damage Event) : Level-1 PRA

PCV failure and radioactive
release : Level-2 PRA

Impacts on the health of
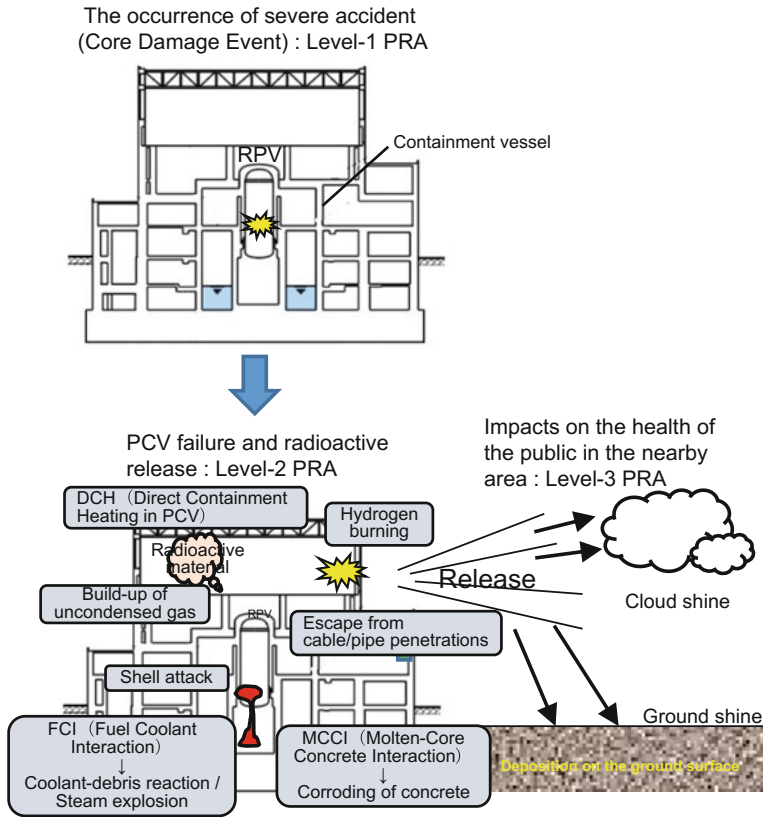the public in the nearby
area : Level-3 PRA

Fig. 8.25 Illustration of PRA

damage states are assigned. When classifying accident sequences into the plant damage states, accident sequences after core damage are carefully studied in terms of how accident progresses and effects on the characteristics of source term. Due considering is given to the fact that the characteristics of accidents due to earthquake are different from those due to random failure of components. This process enables the appropriate characterization of accident sequences. To appropriately estimate the source term in seismic Level-2 PRA, it is necessary to review the condition that is simplified in conventional seismic Level-1 PRA. One of examples is an assumption that failure of reactor building directly results in core damage. An event tree is constructed for the modeling of accident sequences showing how events may develop and lead to release of radioactive materials. Accident sequences in the event tree start from the initial states (the classified plant damage states). Then, this is followed by the determination of the source term for each containment failure mode.
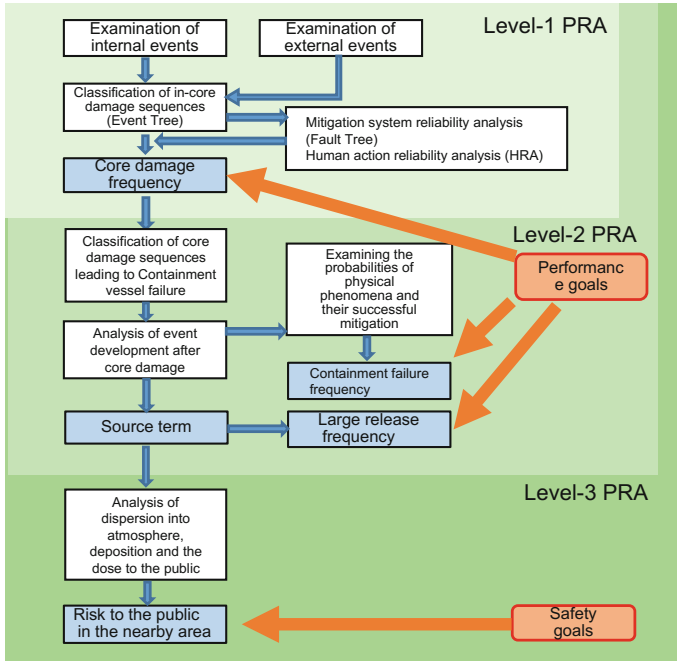
Fig. 8.26 Overview of Level-1, Level-2, and Level-3 PRA

Seismic level-3 PRA, which is to follow the determination of source term, can be implemented basically by applying Level-3 PRA procedures that address internal events.

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