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A Developing Risk-informed Design Basis Earthquake Ground Motion Methodology

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ABSTRACT

Design basis earthquake ground motions for nuclear installations should be determined to assure the design purpose of reactor safety: that reactors should be built and operated to pose no undue risk to public health and safety from earthquake and other hazards. Regarding the influence of seismic hazard to a site, large numbers of earthquake ground motions can be predicted considering possible variability among the source, path, and site parameters. However, seismic safety design using all predicted ground motions is practically impossible. In the determination of design basis earthquake ground motions it is therefore important to represent the influences of the large numbers of earthquake ground motions derived from the seismic ground motion prediction methods for the surrounding seismic sources. Viewing the relations between current design basis earthquake ground motion determination and modern earthquake ground motion estimation, a development of risk-informed design basis earthquake ground motion methodology is discussed for insight into the on going modernization of the Examination Guide for Seismic Design on NPP's in the Nuclear Safety Commission (NSC) of Japan.

KEY WARD: design basis earthquake, earthquake ground motion, nuclear, power plant, seismic hazard, seismic safety, risk-informed design, probabilistic seismic safety assessment.

INTRODUCTION

The seismic safety of reactor facilities is required to assure the reactor safety and radiation protection to the public health and safety by defense-in-depth philosophy for any supposed seismic load occurrences during the reactor operation. The Examination Guide for Seismic Design by the NSC requires that the safety-related structures, systems and components (SSCs) shall be designed to withstand the effects of earthquakes without loss of capability to perform their safety functions in accordance with the classification of seismic importance.

Two types of design basis earthquake ground motions for seismic design are defined. One is derived as the design basis maximum earthquake S1 specified from the past earthquake records and active faults. The other one is derived as the design basis extreme earthquake S2 that exceeds the S1 and would have the greatest effect at a proposed site. However, the sufficiency of the intensity of the current S2 earthquake determination became a controversial problem after the recent inland earthquake experiences such as 1995 Hyogo-ken Nanbu Earthquake Mj=7.2 or 2000 Tottori-ken Seibu Earthquake Mj=7.3. The disasters in the damage belt of the 1995 Hyogo-ken Nanbu earthquake Mj=7.2 that struck the densely populated city of Kobe demonstrated to the public the dangerous power of the near-fault inland earthquakes. The 2000 Tottori-ken Seibu earthquake Mj=7.3 occurred at a previously unknown active fault for which the epicenter was located approximately 45 km southeast from an existing NPP. This caused discussion about the sufficiency of the blind fault earthquake magnitude that is required in the S2 earthquake; commonly a magnitude 6.5 earthquake at the hypocenter distance of 10 km is currently used for seismic design of every exiting NPP. These recent earthquake experiences awoke public concern about the seismic safety of NPPs that the current examination guide considers necessary for review based on the state of the art knowledge of seismology, geology, and earthquake engineering to ensure the seismic safety performance of NPPs from the point of risk managements.

The method to numerically handle the total earthquake effects to the site as probabilistic events is recently evolving in seismic probabilistic safety assessments (seismic PSAs). These systematic examinations are beneficial in identifying plant-specific vulnerabilities to severe accidents to evaluate the risk involved in the seismic safety design of the reactor facilities. Previous results of seismic PSAs for Japanese NPP's by JAERI [1] or NUPEC [2] showed that the reactor core damage occurrence frequency curve has the peak close to the design earthquake levels rather than excessively extreme earthquake level. This suggests the importance of not only the seismic safety assessment for the total earthquake hazard in identifying plant-specific vulnerabilities but also the importance of seismic design for design basis earthquakes including the risk-dominant earthquake level informed by seismic PSAs. The seismic design based on the risk-informed should confirm the integrity of structures and safety functions of the safety-related SSCs by the dynamic response analyses using design basis earthquake ground motions defined including the risk dominant level earthquake that is important to ensure the seismic safety reliability on the seismic design in the face of significant uncertainties.

The seismic safety performances should be confirmed in accordance with the multiple levels of safety conditions complying with the risk information from seismic PSAs to meet the defense-in-depth philosophy. The safety levels that should be assured are: normal operation during high frequency occurrence earthquakes; transient incident of moderate frequency occurrence earthquakes; accidental incident of low frequency occurrence earthquakes. Based on these considerations, severe accident management should be planned for the probabilistic seismic risk. However current deterministic design practice to meet this seismic design requirement is not suitable for thoroughly explaining the relationship between the reactor safety performance and the integrities of structures, systems and components (SSCs). This is because uncertainties both of the seismic hazard among earthquake magnitude, occurrence, ground motion attenuation and of the seismic safety performance within the complex functional structures of reactor facilities.

A probabilistic approach to seismic safety assessment is important from the point of view of "How safe is safe enough." Such an approach takes into account the ground motion from the full range of earthquake magnitudes, allowing explanation of the relationship between the reactor safety performance and the strengths of safety-related SSCs considering the uncertainties within the seismic hazard and the safety performance system. The probabilistic approach to seismic hazard characterization is very compatible with current trends in earthquake engineering and the development of building codes, which have embraced the concept of performance-based design. The objective of the performance-based design is to clarify how reactor safety performance is degrading with the increasing magnitude of earthquakes. Earthquake occurrences are probabilistic events. Design basis earthquakes (DBEs) should consider the effects of every seismic event by occurrence probability to confirm the seismic safety of reactor facilities. Earthquake ground motions are made complex by the effects of the source, path, and site conditions, that is, it can be said the same ground motion will not again.

As experienced the disasters by the near-fault earthquake ground motions of the 1995 Hyogo-ken Nanbu Earthquake, the estimation of the effects of earthquakes to structures is difficult only from the response spectra of earthquake ground motions. The seismic impacts to structures should be evaluated by time domain dynamic response analyses. The adequacy of design basis earthquake ground motions to assure the seismic safety of the complex facilities of NPPs does not suitably explained only by the envelopment response spectrum or a uniform hazard spectrum of seismic sources. The current Examination Guide is under reviewed reflecting the risk insights informed by recent study results of seismic PSAs. The task group on seismic design guide was organized on July 10, 2001 under the Special Committee on Safety Standard in the NSC. In this paper, a methodology of development the risk-informed design basis earthquake ground motions of NPPs is discussed based on the risk information by seismic PSAs compared with the risk insights by the current deterministic design basis earthquake ground motions.

SEISMIC SAFETY BY DEFENSE -IN-DEPTH PHILOSOPHY

Seismic Classification Comply The Defense-in-Depth Philosophy

The seismic safety of NPPs by defense-in-depth philosophy is usually explained in Japan that 1) prevention of abnormal event occurrence, 2) early detection of abnormal event occurrence and mitigation to reduce the influence of the event before it become the accident, and 3) at the accident occurrence, prevent the accident progress and mitigate the accident to reduce the influence by the multiple preparation with diversity and redundancy of the various safety functions of prevention and mitigation systems. If any accident is induced it will be detected quickly and managed to the safety conditions by the safety functions, which hold high reliability due to diversity and redundancy the integrity of safety functions of safe shutdown, safe cooling and containment should be maintained assuming the combination with a random failure of prevention functions and a unit failure of mitigation functions. The seismic design basis requirements defined the performance criterion for the protection against earthquakes that safety related SSCs that are important to assure reactor safety and radiation protection shall be designed to withstand the effects of any supposed earthquakes without loss of capability to perform their safety functions in the seismic design examination guide by the NSC.

The examination guide classified the seismic grades of reactor facilities in accordance with the importance of the safety functions into four classes from high important to low important facilities as called seismic grades As, A, B, and C from the point of the magnitudes of radiation release impacts to environments and public health. The corresponding design basis earthquake ground motions are categorized into four classes from extreme to small earthquake magnitudes considering probability of occurrence frequencies, that are, extreme design earthquake (S2), maximum design earthquake (S1), 1.5 times a non-nuclear facilities design earthquake as the SB, and non-nuclear facilities design earthquake as the Sc so that the integrity of safety-related SSCs required should be maintained, respectively. Each seismic grade facilities are designed to maintain the structural and functional integrities for corresponding earthquakes. Each seismic grade facilities should not be damaged to loss the safety functions by the failure of lower class facilities. The maximum design earthquake S1 is determined based on past earthquakes, earthquakes due to active faults with high activity whose recurrence interval is shorter than 10,000 years. The extreme design earthquake S2 is determined based on the both of seismo-tectonic structures and active faults of high to less activity faults whose recurrence interval is shorter than 50,000 years considering the seismological possibilities of excess the S1 event occurrence based on the characteristics of past earthquakes, active faults and possible blind faults. Current seismic design employed deterministically the seismic source of magnitude M6.5, hypocenter distance X=10 km, to represent the unknown blind faults assuming that could take place at any inland location in Japan. This seismic design requirement is intended to consider sufficient range of earthquakes to assure reactor safety for any potential earthquake shaking.

Plant Safety Levels Related With Seismic Events

In general, earthquake occurrence frequency is higher in the small seismic. As shown in the Figure 1, generally speaking, plant safety conditions might be induced into from slightly abnormal conditions to highly abnormal conditions along with the intensity of earthquake events increased. These abnormal conditions induced by earthquake events should be detected quickly and settled to safety conditions by various safety functions of mitigation. Assuming the combination with a low occurrence frequency/large accident event by random failure, the safety conditions can be induced to severe condition even in a small earthquake. How much the severe earthquake events should be considered and also how much severe event combinations should be considered is therefore become important point in the deterministic seismic design relied on the risk insights. To obtain the quantitative answer to this problem, seismic PSAs might be a useful method to provide adequate solution based on the risk information. The design basis earthquakes also should be defined explicitly the relations with the probability of annual exceedance occurrence frequencies so that the event combinations considering random failures and human factors can be rationally employed for the safety managements in reactor operations.

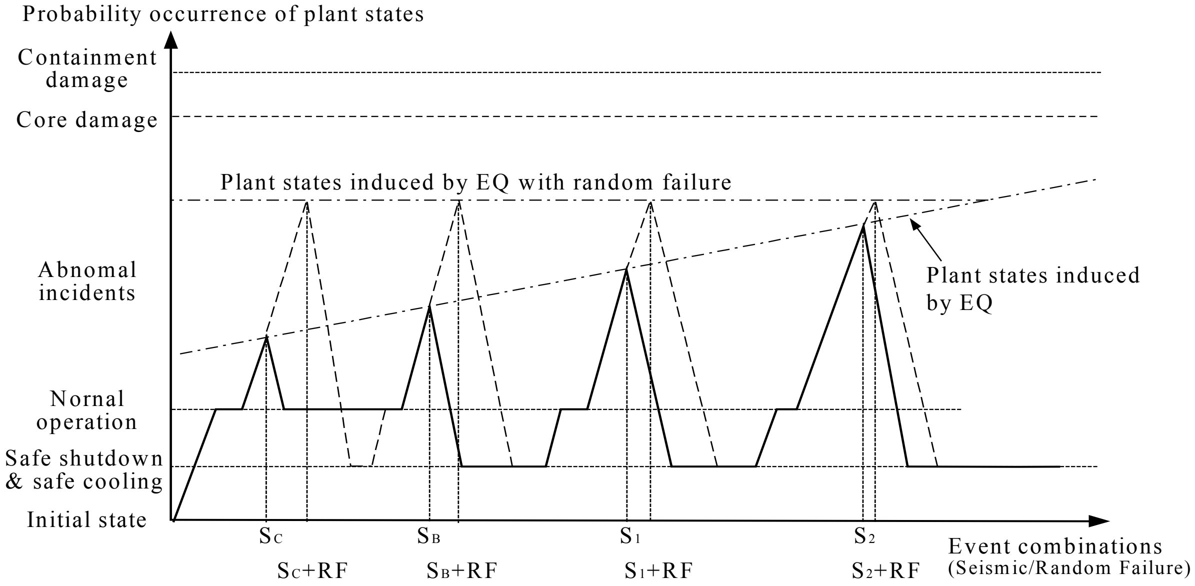


Figure 1 Plant safety levels related with earthquake events. The safety level is higher when the plant states closer to the normal operation.

UNCERTAINTY IN CURRENT SEISMIC DESIGN

Considering the uncertainty of variables, the seismic load and the seismic capacity of a plant can generally be represented by lognormal density functions. The design basis seismic loads and seismic capacity are determined considering the standard deviations, respectively, so that the loads exceedance capacity rates become negligibly small. The seismic loads of structures are derived from the collaborations both of the earthquake ground motions and structure responses. The earthquake ground motions from a seismic source can be predicted many numbers of different ground motions. In the current seismic design, plant-specific safety margin is secured deterministically between the design basis seismic load and seismic capacity based on the engineering judge in the face of risk insights that the safety might not be compromised by uncertainties as shown in the Figure 2. In the deterministic approach, the earthquake ground motion is generally determined as the most likely ground motion of occurrence at a site, such as the mean value derived from the most significant seismic source to a site. On the other hand, the earthquake ground motions might be considered all variations related with the occurrence frequency in the probabilistic approach. The variable range of seismic loads will become larger than deterministic one corresponding the earthquake ground motion variations. The risk of the probability of the seismic loads excess the seismic capacity becomes larger in the case of considering the variation of earthquake ground motions. The design basis seismic loads derived from the earthquake ground motion variations should not exceed the design basis seismic capacity at least in the reliable range of the ground motion variation from the seismological point due to the safety margin included in the seismic design. Current seismic design addresses this qualitatively but does not explicitly perform the quantitative confirmations. The determination of the reliable variation range of the extreme design earthquake ground motion S2 is necessary to explain rationally based on the risk information considering the influences of the uncertainty concerning the seismic safety assured by current seismic design. The accumulation of many strong earthquake ground motion records by the recent densely installed earthquake observations and disastrous earthquake experiences are developing the knowledge on the effects of source rapture process, source and site location relations, and deep soil structures to the earthquake ground motions.

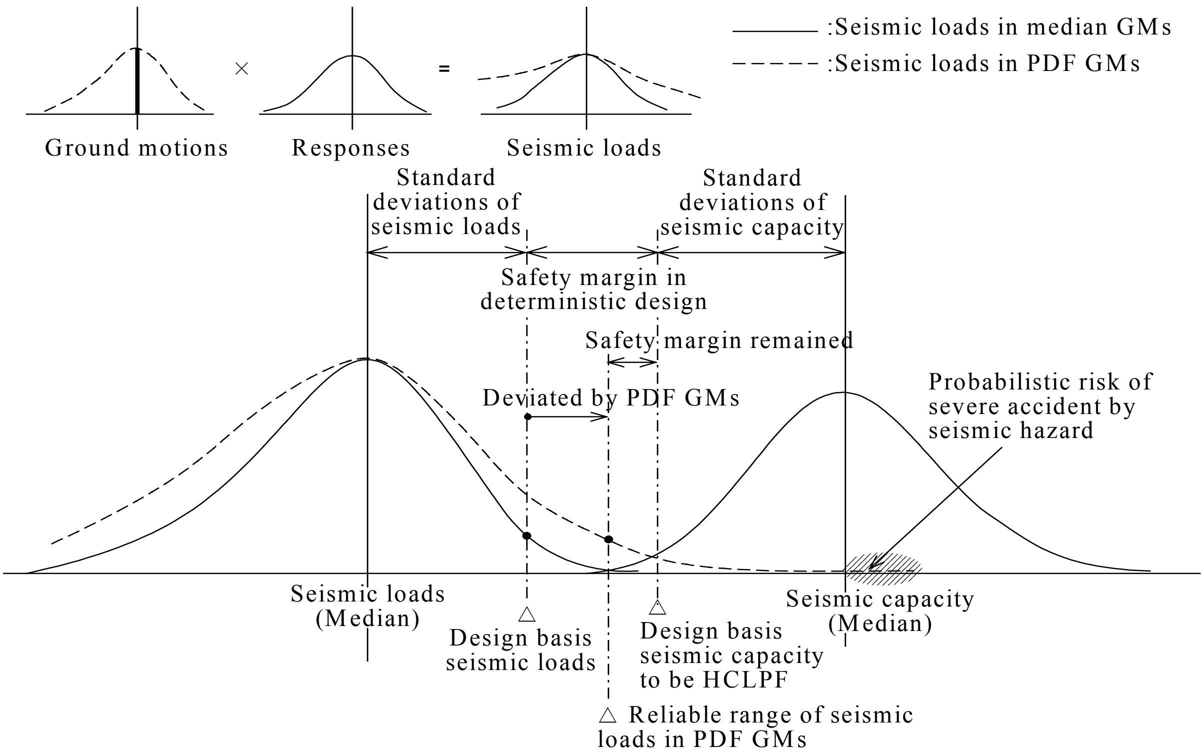


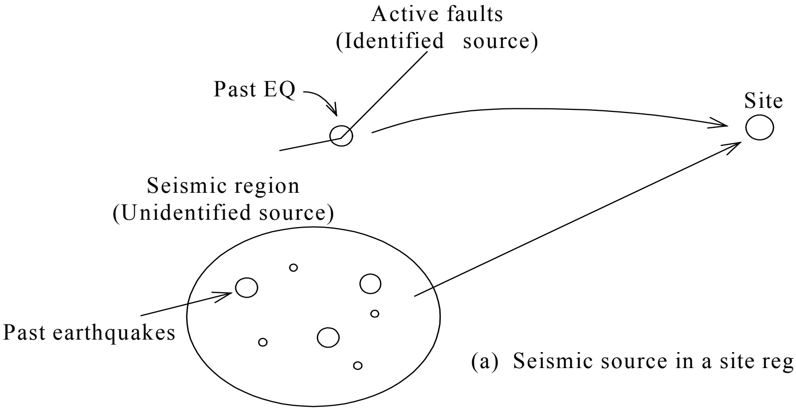
Figure 2 Concept of seismic safety margin in deterministic design. The safety margin should be remained in considerations of the ground motion variability in seismically reliable range.

EARTHQUAKE GROUND MOTION DERIVED FROM SOURCE

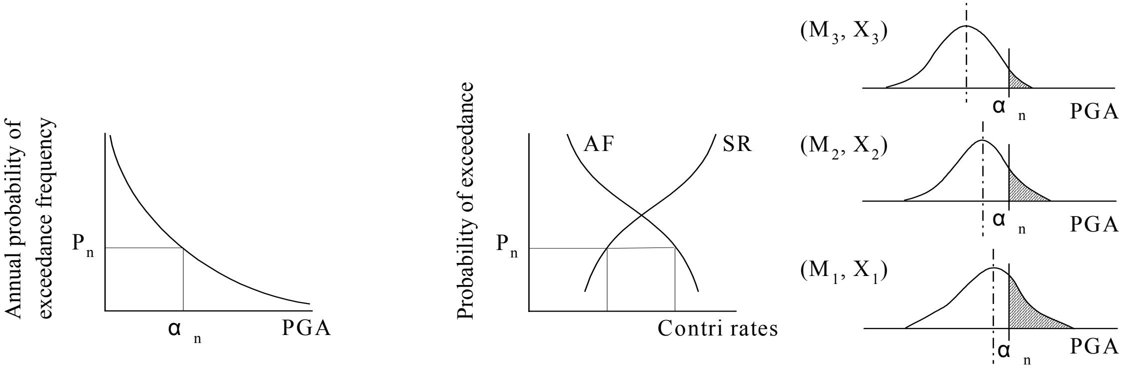
Seismic Hazard And Source Characterization

The earthquake ground motions derived from a seismic source can be predicted many variety of different ground motions. The investigation to identify the characteristics of the sources existing around a site region is important to provide a systematic and comprehensive evaluation of the seismic hazard and its effects on the safe operation of nuclear power plants. Many seismic sources might exist, from the small to large magnitudes and from known active faults to unknown blind faults around a site region. These seismic sources should be characterized based on the past earthquake records, geological and geophysical surveys, and micro earthquake observations. Some of the blind seismic sources might be still remained unknown even after the investigations. As one of the way to represent the effects of seismic sources to a site, a seismic hazard curve is made by defining the annual frequency of exceedance in terms of levels of a ground motion intensity, such as peak ground accelerations, which can be correlated with the damage of critical structures, systems, and components (SSCs) into beyond the current design basis earthquake by the probabilistic seismic hazard analysis. From the site-specific hazard curves, a set of Uniform Hazard Spectrum as recommended in US NRC, may be obtained as the seismic design spectra. One of the objectives in developing seismic design spectra is to achieve approximate uniformity of seismic risk for the safety-related SSCs designed to those spectra, across a range of seismic environments, annual probabilities, and structural frequencies.

As shown in Figure 3, a seismic hazard curve is obtained by the contribution of many sources and the contribution rate of the sources to the annual exceedance of earthquake occurrence frequency is different by each source. The seismic safety assurance into the non-linear range of nuclear power plants consisted with the multiple dimensions and complex systems is essentially required that should be performed based on the dynamic response analyses using time domain earthquake ground motions. However, the determination of the earthquake ground motions from the seismic design spectra such as an envelope spectrum or a uniform hazard spectrum of seismic sources brings up another problem regarding the disconnection with the individual source characteristics. These should also accommodate uncertainty in the site-specific dynamic material properties as well as local and regional seismicity and attenuation characteristics. The determination of an earthquake ground motion to envelop all the prediction is almost impossible. But, development of design basis earthquake ground motions to represent the effective earthquake ground motions could be possible. In order to include the influences of surrounding source effects in to the design basis earthquake ground motions, determination methods using envelope response spectra or uniform hazard spectra of multiple sources are usually employed. In current seismic design it is generally assumed that the DBEs represent the effects of earthquake ground motions by surrounding earthquake sources at proposed site using envelope response spectrum of influential earthquake ground motions with certain margin instead of using all earthquake ground motions predicted. However, the potential variations of ground motion deriver from the envelope response spectrum of the design basis ground motion are not explicitly explained. The relationship between individual sources and the ground motions is not clear in this method. It is not sufficient to represent the earthquake influences only by the spectrum and maximum amplitude of ground motions. The earthquake influences to structures represented by the frequency contents of the amplitudes and phase of acceleration, velocity, displacement, impact force, etc., can be changed by the dynamic characteristics of structures. The seismic capacities of structures are also influenced by the accumulation of fatigue depending on the cycles and intensities of earthquake ground motions. Therefore, earthquake ground motions should be determined to represent the varied amplitude, frequency, and phase characteristics. This can only be done by sufficient numbers of time domain earthquake ground motions.



(a) Seismic source in a site region



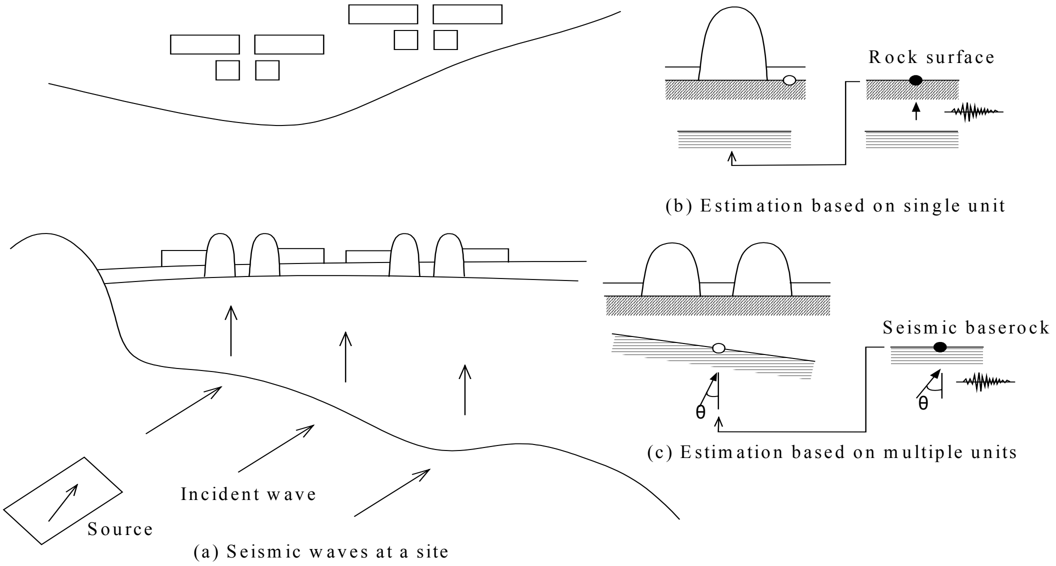
(b) Probabilistic seismic hazards at a site

(c) Soure contribution rates to PHs at a site

Figure 3 Source contributions to seismic hazard at a site. The each source contribution rates are changed according with the probability of exceedance frequency changing.

DBE For Evaluation Seismic Impact On Safety Requirements

Nuclear power stations generally have several reactor units in a site. The earthquake ground motions in a site could vary at the each unit depend on the deep soil structures even though the up coming incident waves are same at the seismic base-rock at a site. The seismic impacts to multiple units in a site regarding the reactor safety and the radiation protection should be assured by the estimation based on the all units in a site. The design basis earthquake ground motions of the each unit are usually determined on the free field rock surface supposed depend on the location of the unit layout basically considering the incident upcoming waves could be defined on the seismic base-rock surface at a site. The reactor safety can be confirmed by the response analyses of each unit. The safety for the radiation protection should be confirmed based on the radiation dose rate by the total release of radiations from the all units in the site. As shown in the Figure 4, the evaluation of the seismic safety on multiple units is preferable to be performed in detail by response analyses using the earthquake ground motions on the seismic base-rock at a site considering the deep soil structures and the unit layout. The seismic response evaluation of a unit using earthquake ground motions defined on the rock surface at a site can be acceptable when the design basis earthquake ground motions at the rock surface is determined conservatively as the representative earthquake by selecting most severe condition for the unit in a site. The evaluation of the seismic safety for radiation protection regarding multiple units is also possible to estimate conservatively based on the summation of the each unit evaluations by the design basis earthquake ground motions defined on the rock surface. However, the estimation method might be too conservative and could be resulted to have excessive dose rate estimation to the public. In order to assure the reasonable radiation protection to the public by the evaluation more detailed, it is preferable to perform the seismic response analyses of the multiple units considering the plant layout using the earthquake ground motions defined on the seismic base-rock surface at a site. The wave reflection and refraction survey to investigate the seismic-base rock in the site can be presents useful information to the determination of the magnitude and location of blind faults.



(b) Estimation based on single unit

(c) Estimation based on multiple units

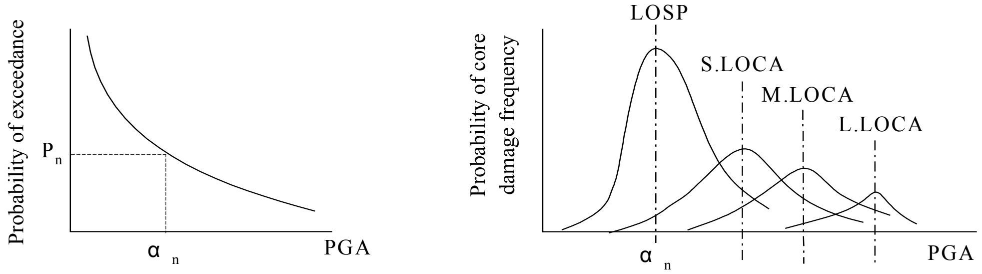
(a) Seismic waves at a site

Figure 4 Earthquake ground motions to estimate seismic impacts at a site.

RISK-INFORMED DESIGN BASIS EARTHQUAKE GROUND MOTIONS

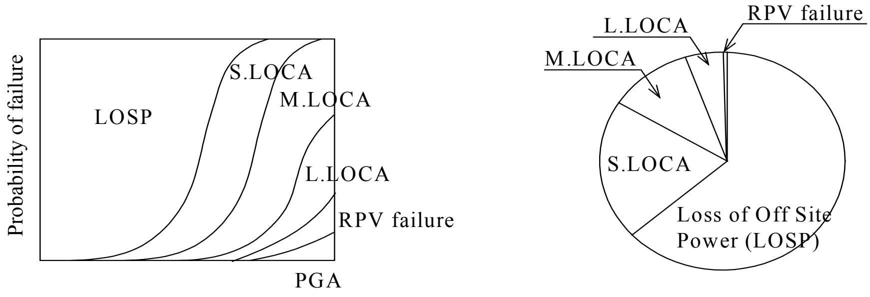
The design basis earthquake ground motions should be risk-informed by the seismic PSA on the proposed site. This is so that the necessity of assuming the extremely large earthquake beyond the design basis earthquakes that could cause the damage of reactor core by the failure of the seismic capacity of almost all safety-related SSCs, is negligible from the point of the risk. The earthquake ground motions should be derived on the source of most significant contribution rate for the risk-dominant earthquake. Identification of dominant seismic risk contributors considering the uncertainties involved are an important process in a seismic design to enhance the reliability of the seismic safety assurance. The current results of seismic PSAs for existing nuclear power plants shows a tendency that the risk of core damage frequency caused by earthquakes are largely contributed by less severe initiating events. The large contribution rate of initiating events are, in the order from larger rate: loss of the offsite power accident (LOSP); small break loss of coolant accident (S.LOCA); medium break loss of coolant accident (M.LOCA); large break loss of coolant accident (L.LOCA); and reactor pressure vessel failure as shown in the Figure 5. The result shows the seismic risk is rather dominated by the failures of less important SSCs than high important SSCs according with the relations of the seismic hazard and fragility curves. The conditional core damage frequency by the each initiating event is shown to become larger along with the seismic load increasing until to show maximum peak at the certain earthquake level and then decreasing the risk curve. It indicates the risk-dominant earthquake is derived in the range of the initiating event of loss of offsite power accident (LOSP). Current seismic PSA can confirm the necessary conditions of reactor safety by secure the success path of safety-related SSCs, but are not yet sufficient to confirm the design basis criteria of reactor safety performances that can be confirmed based on the time domain analyses of reactor behaviors on abnormal operation in seismic events. In order to assure the seismic safety of reactor facilities to the dominant earthquake events, integrities of structures and safety functions of the safety-related SSCs that are necessary to maintain reactor safety conditions in the seismic events should be evaluated by the dynamic response analyses using time domain earthquake ground motions. This is essential to confirm the reactor safety and also the safety for radiation to the public based on the estimation of radiation release derived from the failures of the SSCs.

When the risk-dominant earthquake ground motion intensity is obtained from the peak of the core damage frequency curve estimate, the probability of annual exceedance earthquake occurrence frequency of the dominant level earthquake is decided by the seismic hazard curve estimate. Then the seismic sources contributing the risk-dominant earthquake ground motion intensity are identified as shown in the Figure 6. The method to identify the seismic sources consistent with the occurrence frequency of the risk-dominant earthquake level is available by the studies of Ishikawa and Kameda (1995) [3] or JAERI [4]. The probability occurrence of the earthquake ground motions generated by the sources is distributed as a lognormal density function and the exceedance probability of the risk dominant earthquake level correspond at some deviations apart from the median to low occurrence rate depend on the each source contributions. The design basis ground motions by the risk-dominant seismic source should be derived the two types of ground motions, that are, the most likely earthquake ground motion for the extreme design earthquake S2 by the median exceedance probability and the ground motion by the low exceedance probability to be the risk-dominant earthquake. The risk-dominant earthquake ground motion could be defined newly as the site evaluation earthquake Ss that could be used for the evaluation of the reactor safety by the plant seismic capacity with the criterion of high confidence low probability of failure (HCLPF), and also, for the evaluation of radiation safety to the public based on the radiation release by the failure of safety related SSCs on the multiple units in a site. The studies to obtain the time history of such low occurrence rate earthquake ground motions that is likely large deviated from the median were not much performed and the evaluation method to be acceptable is not yet established. The evaluation methods of such earthquake ground motions should be developed based on the numerical method considering the variation of the source rapture process parameters using seismic fault model. The new, high-quality data recorded in the near-fault region of recent large earthquakes are useful to source characterization such as spatial variations of slip, slip velocity, or rupture velocity for accomplish precise strong motion prediction by modern earthquake ground motion evaluation technology. In the numerical simulation methods to estimate the ground motions, a recipe for prediction of scenario earthquake strong ground motion caused by active fault by means of numerical analysis considering the spatial distribution of fault slip and the time function of slip on the fault has been proposed (Irikura, 2000)[5]. The influences by the factor of the earthquake such as acceleration, velocity, displacement, impact force etc. to the structures are different the significance depend on the dynamic response characteristics of the objectives. The earthquake ground motions to be used in the evaluation of the seismic safety of the reactor facilities are necessary to be derived enough numbers of ground motions to represent the seismic impacts considering the many aspects required for the ground motions depend on the characteristics of objectives.



(a) Seismic hazard curve

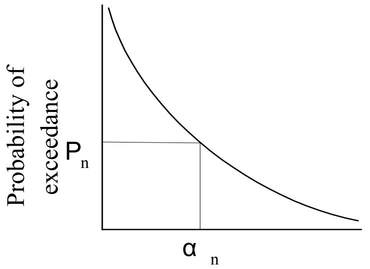
(c) Core damage frequency curves with initating events



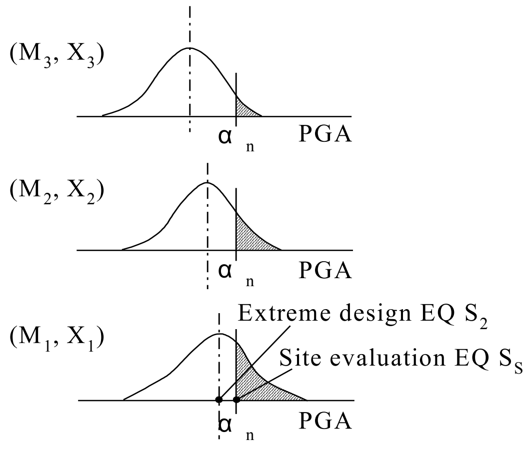
(b) Fragility curves of plant capacity

(d) Contribution rates of initiating events to seismic induced core damage frequency

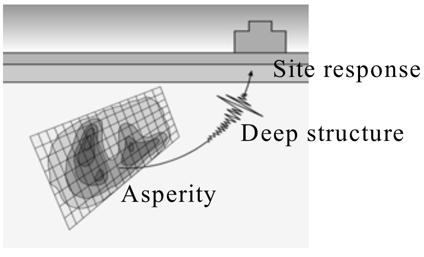
Figure 5 Risk information by seismic PSA



(a) Probability of risk-dominant earthquake on seismic hazard curve



(b) Contribution rates of seismic source to risk-dominant earthquake



(c) Risk-dominant earthquake ground motion prediction by numerical methods

Figure 6 Risk-dominant earthquake ground motion methodology.

CONCLUSION

The seismic design of nuclear power plants should evolve by considering quantitatively the risk induced by earthquakes to be more consistent with the nuclear safety philosophy. Concerning the risk information in a seismic PSA, seismic design should be performed including the risk dominant level earthquake. A development of the risk-informed design basis earthquake ground motions methodology was discussed and summarized here.

First of all, the risk-dominant earthquake level should be identified by the preliminary seismic PSA at the proposed site in the site-licensing phase. If the dominant earthquake level is smaller than the extreme design earthquake the seismic vulnerability should be improved to be beyond the S2.

The extreme design earthquake S2 is not enough to explain the safety beyond DBEs. The DBE ground motions by the risk-dominant seismic source should be used to derive the two types of ground motions that are the most likely earthquake ground motion for the extreme design earthquake S2 by the median exceedance probability and the ground motion by the low exceedance probability to be the risk-dominant earthquake in order to assure the safety beyond DBEs.

The risk-dominant earthquake ground motion could be defined newly as the site evaluation earthquake Ss that could be used for the evaluation of the reactor safety by the plant seismic capacity with the criterion of high confidence low probability of failure (HCLPF), and also, for the evaluation of radiation safety to the public based on the radiation release by the failure of safety-related SSCs on the multiple units in a site.

The numerical evaluation methods are useful for determination the time domain ground motions of the site evaluation earthquake Ss consistent with the probability of exceedance occurrence rate of risk-dominant earthquake by the seismic source of most significant contribution. The time domain earthquake ground motions should be employed, with several different time histories needed to represent sufficiently the seismic impact to the safety-related SSCs.

The seismic performance confirmations by the other design basis earthquakes such as Sc, SB, and S1 defined by the current examination guide are also important for the safety management. The DBEs should be defined explicitly the relations with the probability of annual exceedance occurrence frequencies so that the event combinations considering random failures and human factors can be rationally employed for the safety managements in reactor operations.

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DISCLAIMER

The views expressed in this paper are those of author and should not be construed to reflect the official Japanese NSC position.

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