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A Framework of RI-PB Seismic Design/Part 1: Main Characteristics of the Proposed RI-PB Design and Considerations on Balanced Risk Profile

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ABSTRACT

Japanese current nuclear regulations require traditional deterministic and conservative approach for seismic design. However, application of Risk-Informed and Performance-Based (RI-PB) design leads to a more realistic and rational decision making. For example, RI-PB design enables to show quantitative safety margin for nuclear structures and also shows the effect of various uncertainties. This paper describes the outline of major characteristics of the proposed RI-PB seismic design, which considers quantitative risk index as a design target such as a failure probability of Structure, System and Component (SSC). This paper also describes a case study regarding a Reinforced Concrete (RC) structure for emergency cooling water intake based on the proposed RI-PB framework. The design target of intake structure is determined based on the balanced risk profile of the relevant core cooling system.

BACKGROUND OF THE PROPOSED DESIGN SYSTEM

The importance and significance of the balanced risk profile related to the seismic issues are described in NUREG/CR-7214(2016). Balanced risk profile is essential to secure the nuclear safety in terms of considerations on Defence in Depth (DID). The major reason is that both seismic design and seismic probabilistic risk assessment (PRA) are not a perfect technology, so uncertainties and modelling errors are inevitable. Risk metrics such as Core Damage Frequency (CDF) are used as an important input for the Risk Informed Decision Making (RI-DM). However, if the serious errors subsist in the evaluation, output such as CDF are not only unreliable but also becomes a serious misleading factors for the RI-DM. If a certain Structure, System, Component (SSC) is dominant for the CDF and the errors happen to the modelling and evaluation on those SSC, the results might be totally different from the real situation. Balanced risk profile will be a realistic solution to avoid such a mistake, considering the facts that seismic evaluation is not a perfect technology. Needless to say, balanced risk profile minimizes the error of estimation on risk metrics even if serious mistakes happen to the evaluation on SSCs. NUREG/CR-7214 also describes results of the trial simulations on the relationship between design methodology and balance of the risk profile. Three types of design methodologies are considered, such as current practical design, the latest sophisticated design (ASCE 43-05) and the ideal hypothetical design treatment. It is realized that even the sophisticated design does not bring the balanced risk profile because ASCE 43-05 does not consider system optimization, but considers only RI-PB for each SSCs. Based on those results, NUREG/CR-7214 describes the necessity of the new design system which enables the balance of risk profile.

This paper proposes a framework of RI-PB seismic design system based on the balanced risk profile. Fundamentally, necessity for the risk balance is not limited to the seismic issue but also considerations on risk balancing should be applied to an internal event and other external events as well. However, this paper focuses on the seismic issue because it is one of the major influential risk factors in Japan and the objective of the study is to show the feasibility of the framework. There are still a lot of future works to be conducted for practical use.

This paper describes the outline of proposed RI-PB design system, procedure for balancing risk profile and case study on RI-PB design for RC intake structure as an application example.

OUTLINE OF PROPOSED RI-PB DESIGN

Proposed RI-PB seismic design system is shown in Figure 1. Design Procedure is as follows;

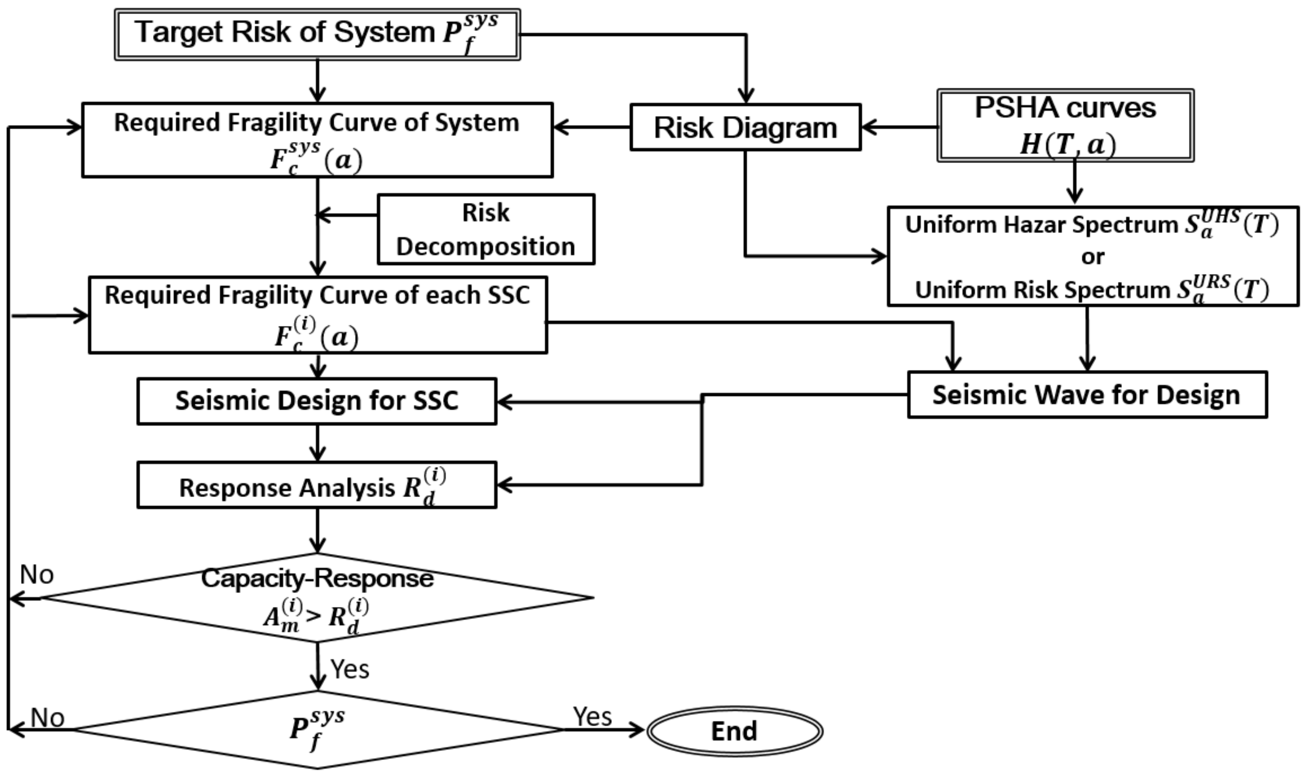


Figure 1. Proposed RI-PB Seismic Design

Step1: Setting of target risk of the system (ex. 10^{-5}/y)
Step2: Setting of a required fragility curve of the system based on the Probabilistic Seismic Hazard Analysis (PSHA) curves and the Risk diagram which will be described later.
Step3: Setting of a required fragility curve of each SSC by risk decomposition process based on risk balancing.
Step4: Conducting seismic design which accommodates to required fragility curve. Seismic design is composed of setting a seismic ground motion based on uniform hazard spectrum/uniform risk spectrum, response analysis and comparison between the capacity and the response.
Step5: Confirmation of failure probability based on designed SSC.

The following are additional information which can help in the understanding of the proposed RI-PB design system.

Nakajima et al. (2010) developed a seismic risk diagram which relates failure probability, required structural capacity and quantitative uncertainty, based on PSHA curves at the target site utilizing the following equation.

$$P_F = \int_{Amin}^{\infty} \frac{dF_c(X_m,\beta,a)}{da} \cdot H(a)da \tag{1}$$

Where Fc is Fragility curve which is a function of *Xm* (median capacity), β (quantitative uncertainty) and α (peak ground acceleration) and *H(a)* is the seismic acceleration on the PSHA curve.

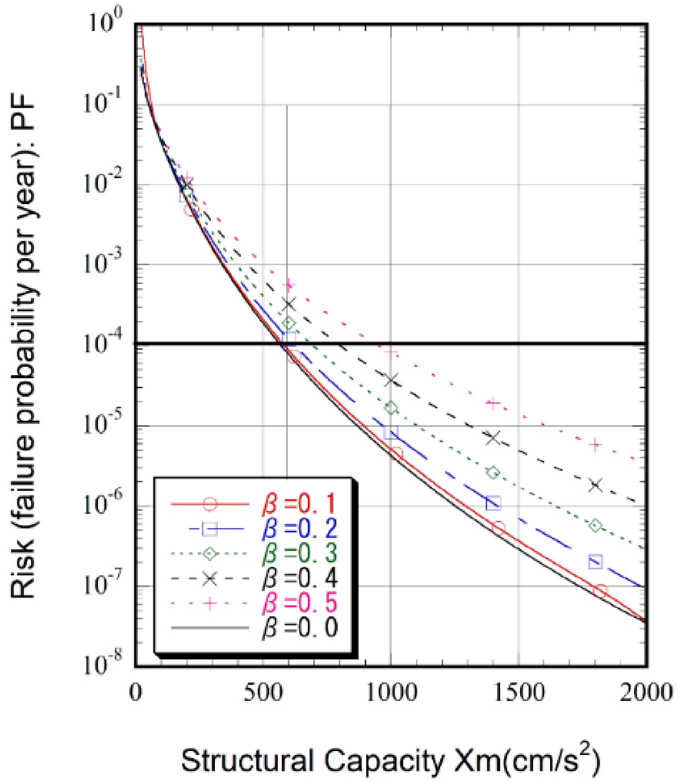


Figure 2. Risk Diagram

Figure 2 is an example of risk diagram. A solid black line (β=0) corresponds to a PSHA curve. Required structural capacity (median capacity) is obtained by supposing β which is uncertainty of the fragility curve. As shown in Figure 2, this example illustrates that required structural capacity should be less than the seismic motion of 1000 Gal if the required failure probability is 10^{-4}/y and β is smaller than 0.5. The larger β is, the more failure probability would be for the same *Xm*. The larger β is, the more structural capacity would be required for the same failure probability. Although it is difficult to estimate uncertainty of fragility curve before the detailed design, it has been recognized that uncertainty of SSC's fragility curves is generally 0.2-0.4. Therefore risk diagram is useful for the basic design stage.

In the proposed RI-PB design framework, system fragility curve is obtained based on the PSHA curve, required failure probability such as 10^{-5}/y and supposed β. β=0.4 is adopted in the following case study because a larger β brings conservative fragility curves.

METHOD OF RISK BALANCING

Ohtori et al. (2021) proposed a methodology for risk balancing using Event Tree (ET) and Fault Tree (FT) which are used in PRA system analysis, referring the Portfolio theory. They developed the balancing methodology considering the fact that “Balancing of the risk profile” means “Minimization of variability of failure probability of each SSC”. Therefore, similarly to the portfolio theory whose basic policy is to minimize investment risk through diversified investments, they considered minimization of variability of risk index as an objective function for numerical calculation. They conducted a trial calculation utilizing ET and FT which are shown in Vaishanav (2020). Its number of event sequences of them is 8, which are composed of 25 basic events. Ohtori et al. (2021) selected Fussell Vesely (FV) and Risk Achievement Worth (RAW) as risk balancing index, which are usually used in PRA as index of contribution of each SSC to total risk such as CDF. FV indicates the degree of improvement of the risk index (ex, CDF) when it is assumed that concerning SSC never loses its function. On the other hand, RAW indicates the degree of increase in risk index (ex, CDF) when the concerning SSC is assumed to fail.

Ohtori et al. (2021) shows the balancing results by comparison between FV and RAW before and after the balancing treatment. The changes in FV and RAW before and after the balancing risk process for probability estimation of Loss of Coolant Accident (LOCA) are as shown in the Figure 3. It is observed that variability of FV and RAW became smaller as a whole. Ohtori et al. (2021) adopted ideal numerical condition, that is, ideally all SSC’s FV and RAW will be balanced. However, this is nearly impossible in a practical situation because safety criteria and failure mode of each SSC are different. Considering such practical situation, risk balancing method by Ohtori et al. (2021) contrives so as to extract SSC which should be balanced according to the realistic design criteria.

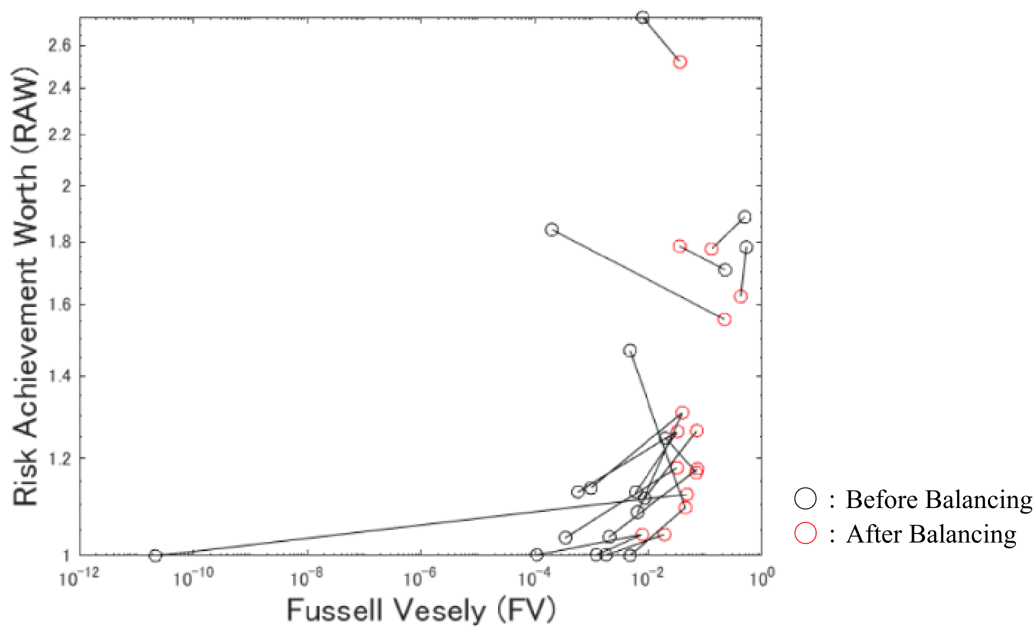


Figure 3 Changes in FV/RAW before and after balancing

CASE STUDY

A case study was conducted to confirm the feasibility of the proposed RI-PB framework. The case study was conducted at a hypothetical site in Miyagi prefecture as shown in Figure 4, which is located in North eastern region in Japan. The seismicity of Miyagi is relatively higher in Japan because the plate boundary between Pacific plate and Eurasian plate is nearby the site. As a matter of fact, the huge Tohoku earthquake with a magnitude of 9.0 in 2011 occurred along the plate boundary. In addition to the subduction type earthquakes, shallow crustal earthquakes due to active faults are also expected to occur in this area.

PSHA curves and seismic risk diagram (β=0.4) at Miyagi site are shown in Figure 5. Headquarters of Earthquake Research Promotion (HERP) has developed PSHA curves in Japan and has published the results. We utilized HERP's PSHA curves, but modified the ground condition at Miyagi site so as to accommodate the ground condition of Japanese NPP citing criteria. According to the Japanese nuclear seismic criteria, both design basis ground motion and PSHA curves must be defined at a rock foundation whose shear velocity (Vs) is faster than 0.7 km/sec.

The case study was conducted according to the proposed design flow as shown in Figure 1. At first, we developed a PSHA curve and then obtained risk diagram by supposing β as mentioned above. We applied the proposed RI-PB design framework to reactor emergency core cooling system including RC emergency intake structure. Based on the risk diagram, we were able to develop the system fragility curve. Then, we obtained the fragility curve of the target SSC by risk balancing method. We selected RC intake structure as a design target because seismic force is dominant for the design of RC intake structure and feasibility should be clarified easily rather than other SSC such as RCW, RSW and others whose design dominant factors are not only limited to seismic factors. After we obtained the required fragility curve for intake structure, we developed the seismic ground motion which accommodate both PSHA and risk diagram, and then conducted a response analysis as usual seismic design.

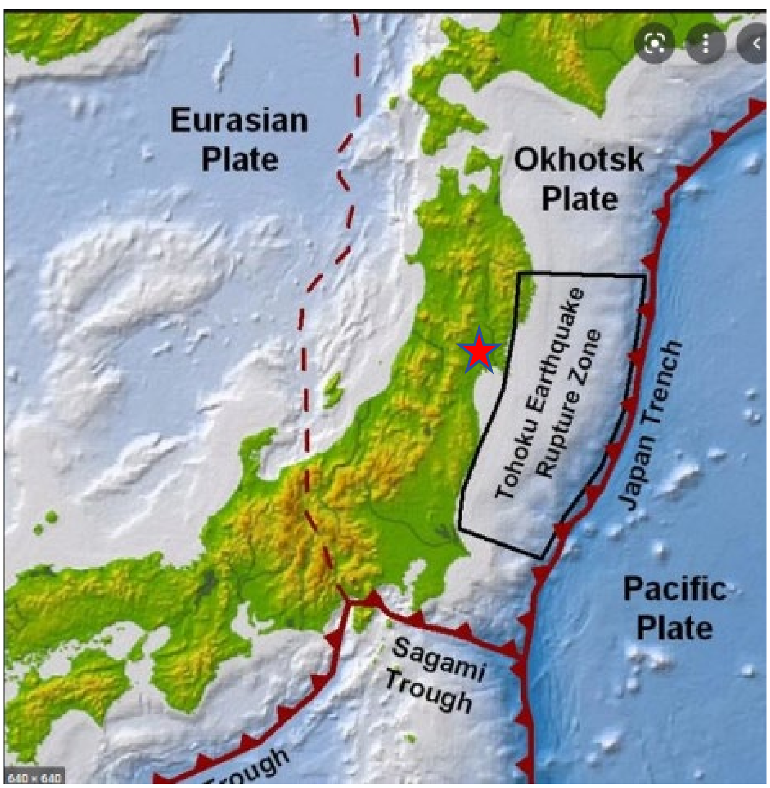


Figure 4 Location of Miyagi

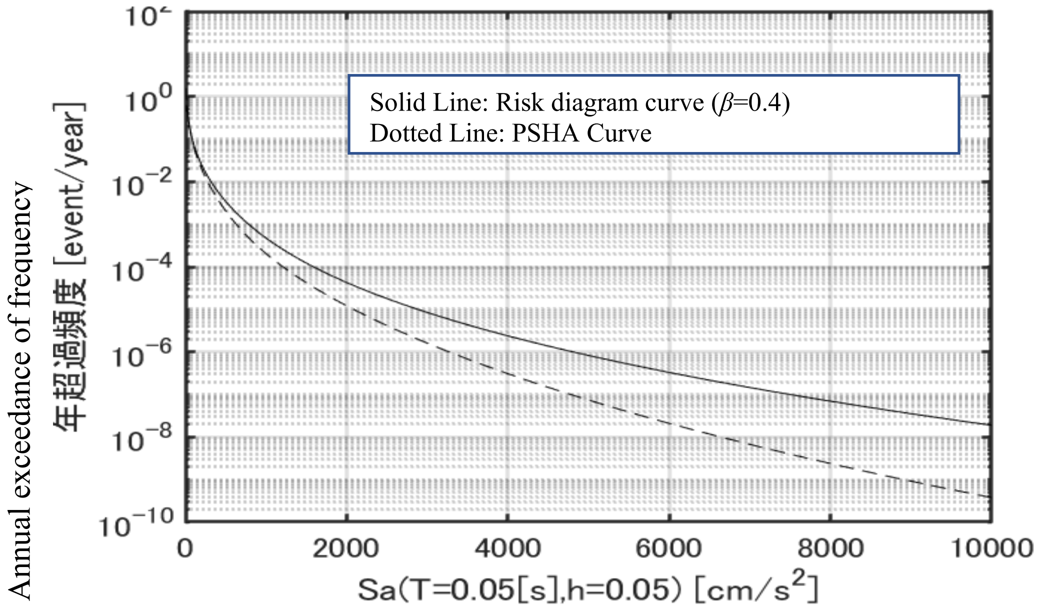
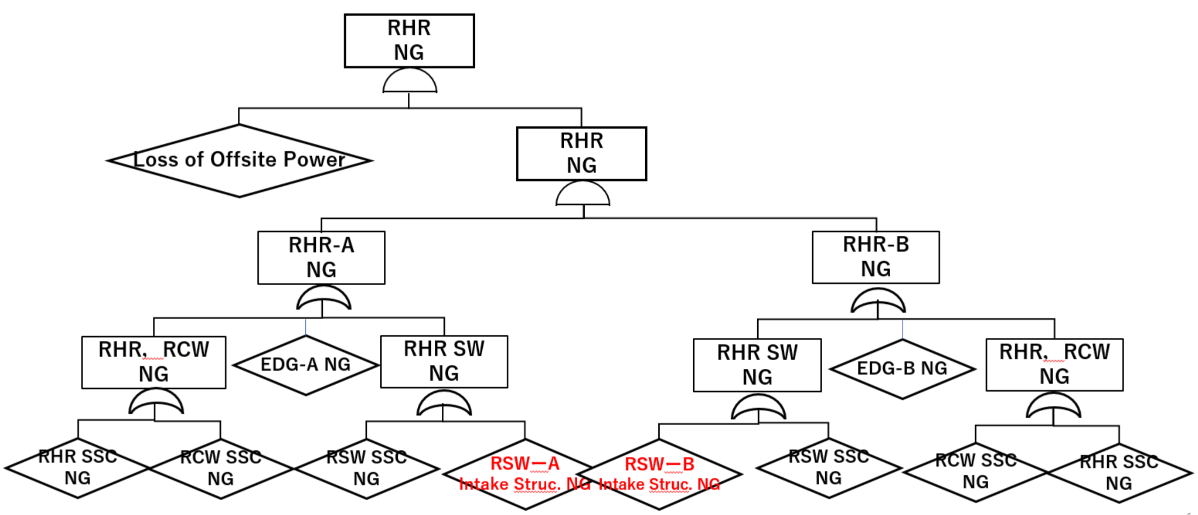


Figure 5. PSHA Curve and Risk Diagram (β=0.4) at Miyagi

As illustrated in Figure 5, seismic response at T (period) =0.05sec corresponds to 1.2g at event frequency of 10^{-4}/y and required capacity at 10^{-4}/y which corresponds to median capacity of fragility curve is 1.5g. The case study handles Emergency Reactor Core Cooling System including intake structure. Its FT is shown in Figure 6.



RHR: Residual Heat Removal System
RCW: Reactor Building Closed Cooling Water System
EDG: Emergency Diesel Generator
RSW: Reactor Sea Water System

Figure 6. FT of the System

The target failure probability of the whole RHR system was set as 10^{-5}/y in this case study. We suppose intake RC structure for RHR-A and RHR-B is common according to the current practical design and construction. Based on the risk balancing methodology, required fragility curves were obtained as shown in Figure 7. The system fragility curve was obtained from the risk diagram. Since the example system has A and B systems in parallel, the required fragility curve is weaker than that of system. On the other hand, the fragility curve of intake structure is stronger than the system because the intake is shared structure of A and B systems.

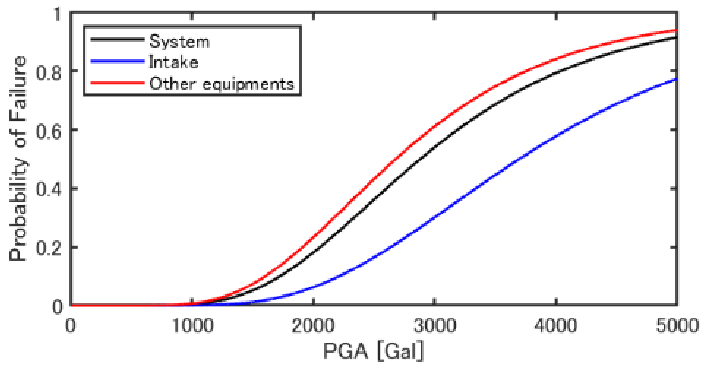


Figure 7. Fragility curve

The next step was to determine the seismic ground motion for the response analysis of RC structure based on the required fragility curve, PSHA curve and Risk Diagram. Based on the required failure probability at the median point in the fragility curve, time history of seismic ground motion was obtained. Obtained time history of ground motion which corresponds risk diagram is shown in Figure.8. When we developed the ground motion, uniform risk spectrum was utilized as shown in Figure 8.

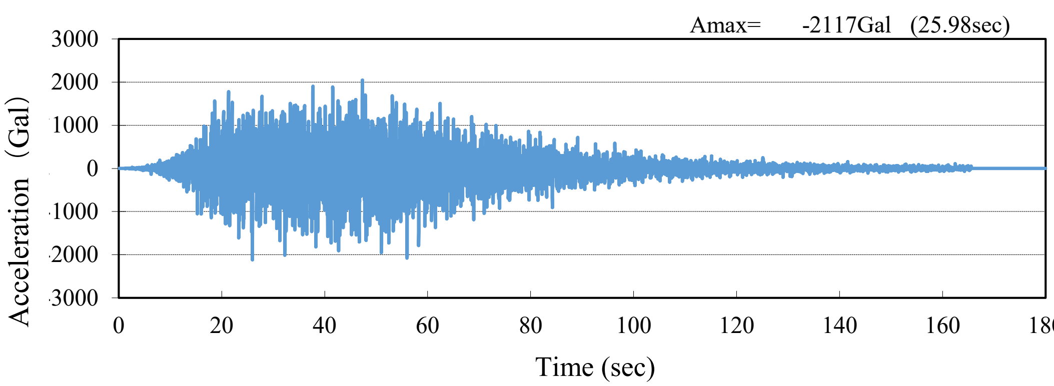


Figure 8(1) Time history of ground motion

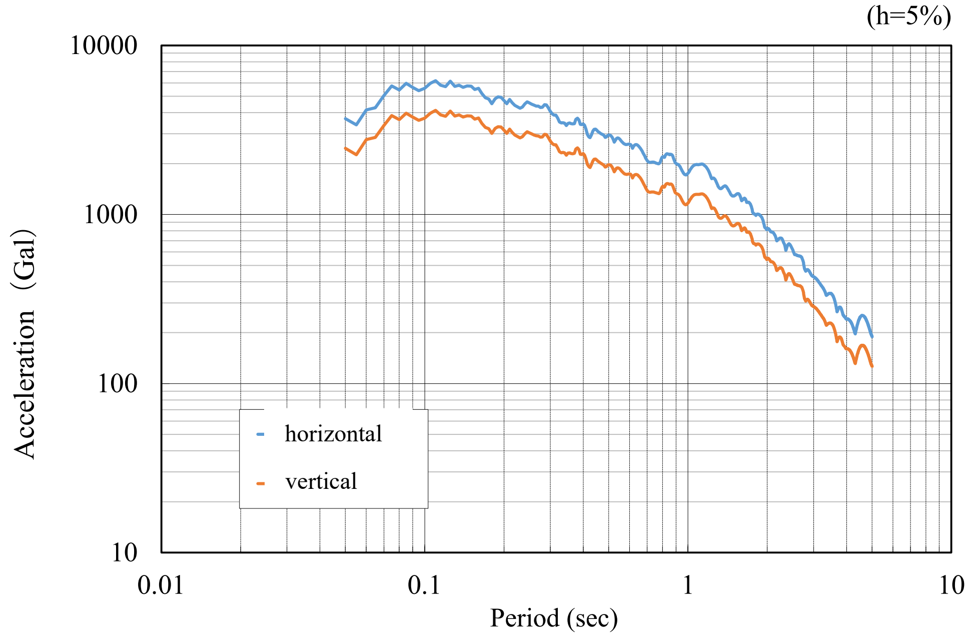


Figure 8(2) Uniform Risk Spectrum

Response analysis was conducted by current Japanese practice in the nuclear industry. Details of modelling and numerical simulation are not described in this paper because the objective of this paper is to show the feasibility of the RI-PB design framework. However, minimum information for response analysis is described below. Response analysis was conducted utilizing TDAPIII which deals with non-linear characteristics of RC structure and ground. RC structure and ground were modelled utilizing beam element and solid element respectively. Non-linear characteristics of RC structure and ground were considered utilizing M-φ (Moment- curvature) relationship and Ramberg-Osgood model respectively. FEM model for response analysis and material property are shown in Table 1.

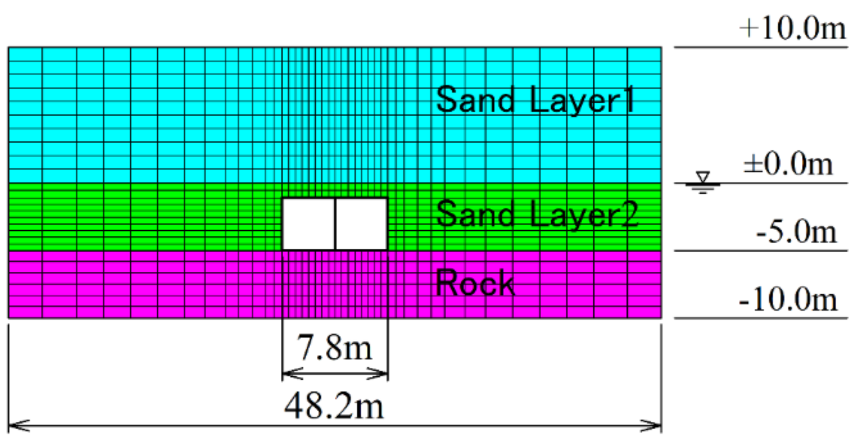


Figure 8. Model for Response analysis

Table 1 Material Property

Soil Layer	Unit Volume Weight γ (kN/m^3)	Poisson's Ratio ν	Shear Wave Velocity V_s (m/s)	Initial Value of Shear Modulus G_0 (kN/m^2)	Initial Value of Damping Constant h_0 (%)
Sand Layer 1	18.0	0.40	300	165,000	2.0
Sand Layer 2	20.0	0.48	300	184,000	2.0
Rock	20.0	0.33	700	1,000,000	2.0

The comparison between capacity and response is shown in Table 2. One of the problems related to RI-PB seismic design is identification of realistic capacity. According to the current design practice of RC structure in Japan, deformation angle (between top and bottom) is utilized as a criterion. Specifically, 1% of deformation angle is utilized as a design criterion based on the great amount of experiments. However, 1% is a criterion for the design, which includes large conservatism. If 1%. RI-PB design should done utilizing realistic response and realistic capacity and criterion should be considered by failure probability such as 10^{-5}/y, 10^{-6}/y. Under 1.0 in Table 2 means accommodation to the current conservative design criterion. On the other hand 1.0<2.0 in Table 2 means design is completed if the criterion of deformation angle is 2% as a realistic capacity. Steel ratio <0.2% is not allowed by the general RC structure regulation in Japan.

Table 2 Design Result

Thickness (cm)	Steel	Steel Ratio (%)	Criteria (Safety Factor based on the current design practice)
100	D16@150	0.13	Steel ratio <0.2％
	D19@150	0.19	Steel ratio <0.2％
	D22@150	0.26	1.637
	D25@150	0.34	1.563
	D29@150	0.43	1.450
	D32@150	0.53	1.276
	D35@150	0.64	1.105
	D38@150	0.76	0.956
	D41@150	0.89	0.865
	D51@150	1.35	0.705

D@@150：Diameter of steel = @@mm, distance between steels=150mm

CONCLUSION

We proposed RI-PB seismic design framework considering the risk balance of the system. Balance of the risk profile is essential to secure the nuclear safety because uncertainties and modelling errors are inevitable in the evaluation. Balancing the risk is achieved by the considerations on minimization of CDF contribution such as FV and RAW. On the other hand, system fragility is obtained risk diagram. Based on the system fragility and balancing the risk, required fragility curves should be obtained. Then deterministic seismic design is possible with the ground motion which accommodates required fragility curves and risk diagram.

One of the key challenges for future development is the combination of design factors. This paper proposed a framework for a seismic issue. However, there are many factors to be considered during the design stage other than seismic issues. Another challenge is capturing a realistic capacity. RI-PB design should be conducted by using realistic response and realistic capacity and necessary conservatism should be considered by using the appropriate number of failure probability.

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