Research on Seismic PSA for NPPs

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Abstract: More and more attention has been paid to Seismic PSA (Probabilistic Safety Assessment) in nuclear power plant especially after Fukushima accident in March 2011. However, new method for Seismic PSA should be developed since the equipment failure probability is largely the function of PGA (peak ground acceleration) which is given by a probabilistic density curve. One useful method to deal with the conditional probability is to divide the seismic hazard curve into several intervals. In this paper the analysis frame for seismic PSA is first introduced. Based on this analysis procedure, we obtain the consequence by the fault trees and event trees modeling and fragility input. Finally, by using the two assumptions, PGA intervals and ceiling factor are compared. The obtained results and insights are sensitive and significant to the CDF (core damage frequency). However, the seismic risk of the plant below SSE is relatively low, where the contribution of the interval between 0.3g and 0.45g has the most significant effect.
Keywords: Seismic PSA; PGA; conditional probability; seismic hazard curve

1 Introduction

In April 2004, the Chinese Nuclear Safety Administration issued new HAF102 <safety regulations for design of nuclear power plant>, where the HAF102 clearly requires that probabilities and consequences of nuclear power plants caused by various external disasters (especially those disasters related to the individual sites of nuclear power plants) must be evaluated broadly [1].

In March 11th, 2011, a big earthquake happened in Eastern coast of Japan near the Fukushima Nuclear Power Plant, when the highest tsunami by the earthquake hit the plant, had brought about a series of severe accidents in the Fukushima Nuclear Power Plant. This Fukushima Daiichi nuclear plant accident was a wake-up call for all the nuclear power industries around the world. It had made a major shift of nuclear safety concepts in the United States, France, Germany and other countries in order to take great attentions on the consequence of severe accidents in nuclear power plant, especially to reconsider emergency preparedness and the effect of external disasters caused by severe accident.

In 2012, Chinese Nuclear Safety Administration developed "safety requirements for new generation nuclear power plant and prospective targets of 2020", in which the Chinese administration put forward the requirements for the quantitative objectives of nuclear safety. This was the qualitative change of the status of the PSA (probabilistic safety analysis) technology in China. As the results, the practice of full scope PSA has become indispensable for Chinese nuclear industries for both the nuclear power plants in operation and the new nuclear power plants in designing.

In this paper, the analysis frame for seismic PSA is analyzed first. Then, the seismic hazard analysis and seismic fragility analysis are done and a seismic PSA model of the plant is developed. With quantification of the seismic PSA model, seismic risk of the plant is obtained and risk insights are discussed. Based on the analysis in this paper, seismic risk of the plant is relatively low and the contribution of the interval between 0.3g and 0.45g is the most significant.

2 Current situations in China for practicing Seismic PSA

From the domestic practice, nuclear power plants under construction in FSAR (Final Safety Analysis Report) stages or before fuel loading have completed the seismic margin analysis (SMA).They are preparing for the seismic PSA. New three generations and new design nuclear power plants carry out the

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seismic PSA in PSAR (Preliminary Safety Analysis Report) stage. Up to now, no domestic utility has submitted official seismic PSA report to the Chinese Nuclear Security Administration.

Earthquake may lead to multiple events occurring at the same time and hugely threaten the safety of nuclear power plants. Therefore, it is very necessary and urgent to carry out seismic PSA. Through the study evaluation of power plant response to the earthquake, and the assessment of important personnel actions which have dominant contribution to CDF (Core dame frequency), to realize the seismic quantitative risk. In addition, seismic PSA can support nuclear power plant risk informed decision making using the performance index, which has important significance and application value for optimizing the allocation of resources while improving the weakness.

3 Method research

Seismic PSA analysis is a comprehensive project, which includes Seismic hazard analysis, Seismic fragility analysis, Plants response analysis and Seismic PSA quantitative analysis [2-3]. All kinds of tasks as shown in Fig. 1 for the flow chart will not be made in timely order. They need iteration if necessary according to the process of proper analysis.

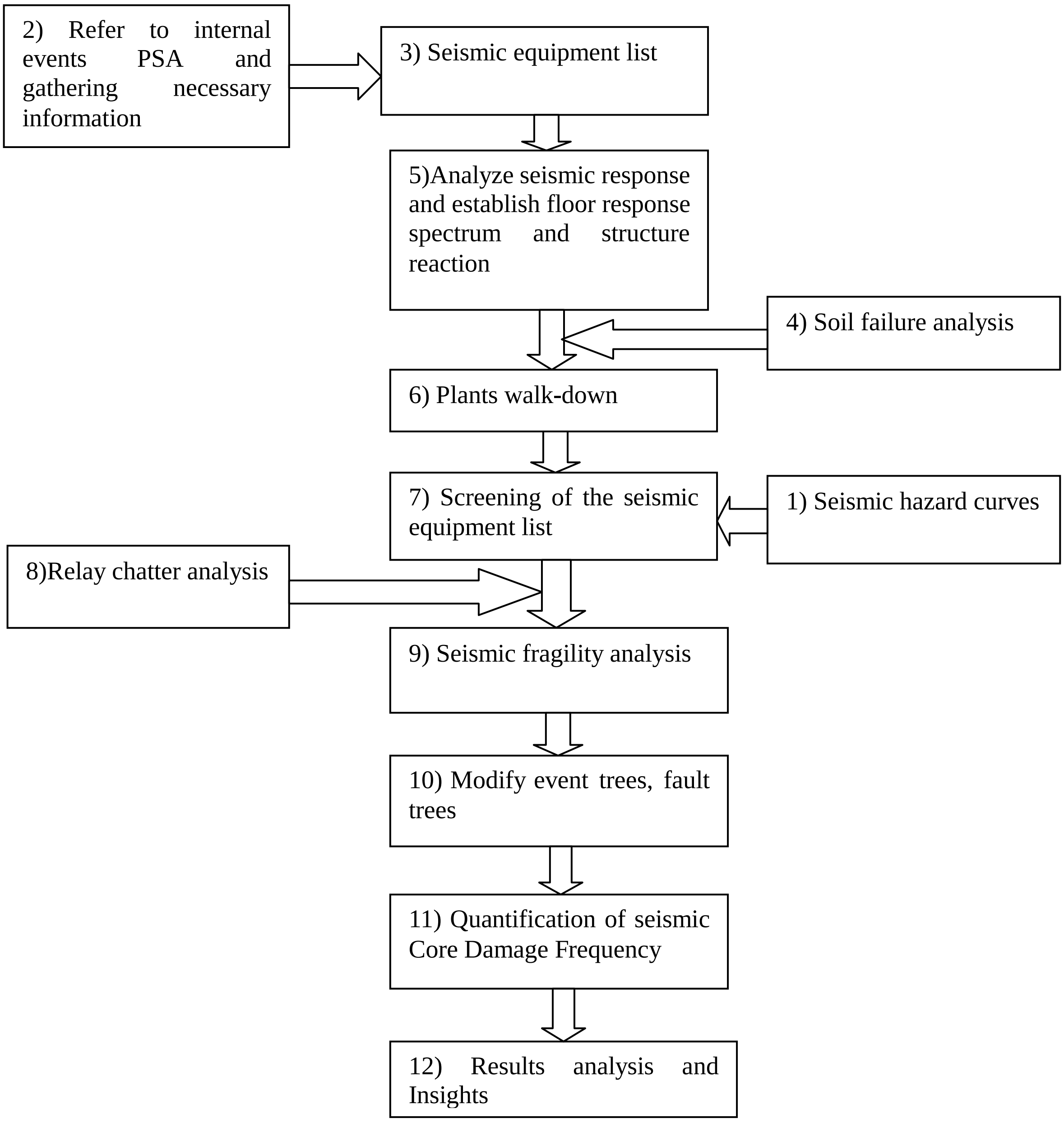

Fig. 1 Seismic PSA task frame.

Through investigation and carrying out seismic PSA work, the analysis method of disasters, analysis scope and concerns of earthquakes PSA have significant difference with the internal events. Seismic PSA has its particularity. We must consider all possible earthquake magnitude and evaluate their frequency and consequent damage to the systems and equipment. As multiple redundant equipment failure simultaneously under Earthquakes and spatially interact, we need actual design data, operation records and walk down to make sure the impacts of earthquake on nuclear power plants.

4 Research subjects on Seismic PSA

4.1 **Seismic hazard analysis**

Probabilistic seismic hazard analysis (PSHA) is to get seismic hazard curves of the site of nuclear power plant. The seismic hazard curve indicates the annual exceedance frequency at different ground motion level of earthquakes and the relevant uncertainty information[3], which usually include a set of curves annual exceedance frequency between 1.0×10^{-3}～1.0×10^{-7}/year and at 5%, 15%, 50%, 85%, 95% confidence level.

The following Fig. 2 shows 1728 the annual exceedance frequency curves of a specific pressurized water reactor nuclear power plant [7].

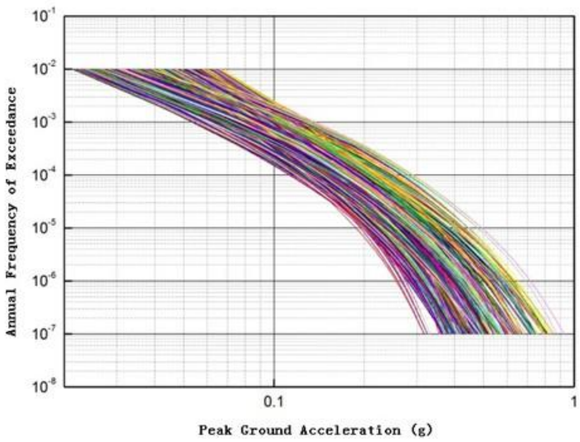

Fig. 2 Seismic hazard curve diagram.

4.2 Seismic Fragility analysis

The seismic fragility analysis is assumed to be conducted by group discussion of the experts of different domains such as the structure, mechanical equipment, electrical and instrument control equipment analysis experts, as are described in the references of EPRI 1002988[4] and EPRI103959 documents [5]. By quantitative screening and classification, finally six plant buildings, such as Reactor building, electrical building, *etc*., and 50 kinds of equipment, such as pumps, valves, water tanks, *etc.*, are made the specific calculation to complete the PSA quantitative analysis.

A seismic walk-down for the plant is done to complete the fragility analysis and necessary information is collected. The results show that the condition of the seismic design for structures and equipment is very good.

4.3 Modeling and quantitative analysis of seismic PSA

By using commercial software, such as RiskSpectrum and HazardLite, this is developed by Lloyd's Register Consultation Company[8]. The authors of this paper established the seismic PSA model of mega-kilowatt class nuclear power plant. According to the response of nuclear power plant under earthquake, event tree/fault tree logic models were set up for various SSCs (systems, structures and components) whose failure may cause core damage accidents.

4.3.1 Seismic PSA initial events sequence

Generally, there are multiple Seismic PSA modeling methods with their associated analysis software. In China mainly small event tree-large fault tree method is employed for seismic PSA. Seismic PSA mainly adapts pre-event tree method to analyze the accidents caused by earthquake which is similar to initial events which include all kinds of combination of initial events. Then mitigation event trees and fault trees are built according to the consequence in seismic pre-event trees. The seismic pre-event tree model is shown in Fig. 3.

4.3.2 Seismic PSA Event trees and fault trees analysis

According to the seismic pre-event tree, 15 categories initiating events are established by sorting, which include 8 categories combination events. For each category initiating event you need to develop event sequence analysis based on level 1 PSA event tree model, by considering mitigation system and its supporting systems, where you need to include seismic failure caused by seismic, the random failures and human errors.

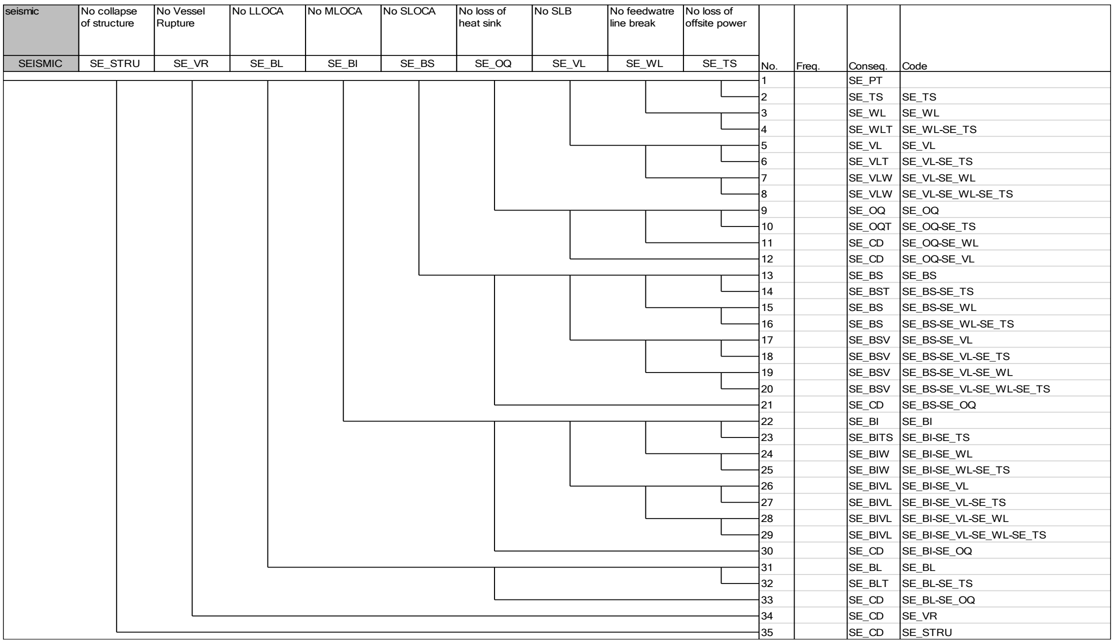

Fig. 3 Seismic pre-event tree.

We add the seismic equipment list of structures and equipment failure to the fault tree model. In different intervals of ground motion acceleration, the conditional probability of seismic failure is different. Therefore, we need to establish seismic failure basic events respectively by setting exchange events and house events to give different failure probability under different ground motion levels.

For the basic structures and equipment seismic failure events, we need to consider correlation of seismic failure between identical equipment. Under the earthquake, all the SSCs at the same time have the same ground motion input. The identical equipment located in the same building elevation is affected by ground motion equally. And usually assuming the dependency of the identical equipment is 100%, that is, if one equipment failure due to earthquake, the other equipment will be complete failure simultaneously, especially for the redundant equipment of the systems, 100% correlation is considered in the fault tree modeling by using the same basic event for them.

4.3.3 Quantification of Seismic PSA model

Seismic PSA quantitative analysis is the integrated results of seismic hazard analysis and seismic fragility. Combined with the quantitative calculation of seismic PSA model, we can get the CDF with the evaluation of the uncertainty. Based on seismic risk of different intervals of ground motion acceleration, the quantitative calculation of the convolution of seismic risk curve and seismic fragility curve will be carried out by using software of Risk Spectrum in order to obtain nuclear power plant seismic risk insights from the results.

Convolution of seismic risk curve and seismic fragility can be represented by Eq. (1) [6],

$$CDF = -\int_0^{+\infty} F(a)\frac{dH}{da}\,da \qquad (1)$$

Where the term $F(a)$ represents power plant level earthquake fragility curve, and the differential term $\frac{dH}{da}$ is given by differentiation of the seismic hazard, H, with the peak ground acceleration, a. Very low magnitude earthquake is not enough to threaten the safe operation of nuclear power plant. Under high magnitude earthquake, it will usually cause the nuclear power plant a wide range of serious damage with a probable direct result of core damage and radioactive release. But since the occurrence frequency of this kind of big earthquake is very low, its contribution to the total risk is relatively low.

5 Results and discussion

5.1 Results

5.1.1 CDF for different intervals of ground motion acceleration

According to methodology, quantitative screening criteria and the quantitative analysis requirements of EPRI 3002000709[3], this paper selects the 16 acceleration intervals. The results and the overall seismic acceleration interval CDF are shown in Table 1.

We can see from Table 1 that (i)CDF is 2.73×10^{-6} /reactor*year, PGA **(peak ground acceleration)** between 0.3g～0.45g, and that (ii)the corresponding seismic risk contribution is the highest percentage, that is, nearly 50% contribution to the seismic PSA CDF. CDF under Safety Shutdown Earthquake(SSE), 0.2g is 1.15×10^{-7} /reactor*year, nearly 4.2% contribution to the total seismic PSA CDF, the contribution is very small. When it happens seismic below SSE, it is very safe for the NPPs.

To further compare earthquake risk contribution for different acceleration intervals, the acceleration interval seismic induced CDF average histogram is set in Fig.4. And all the sensitivity analysis compare with this histogram.

5.1.2 Initiating events contribution

Table 2 shows initiating events CDF contribution. While Fig. 5 shows the pie chart for initiating events category.

The following Table 2 and Fig. 5 show that Loss of off-site power and Loss of emergency AC power are the highest. The two categories contributions are 60% to the total CDF.

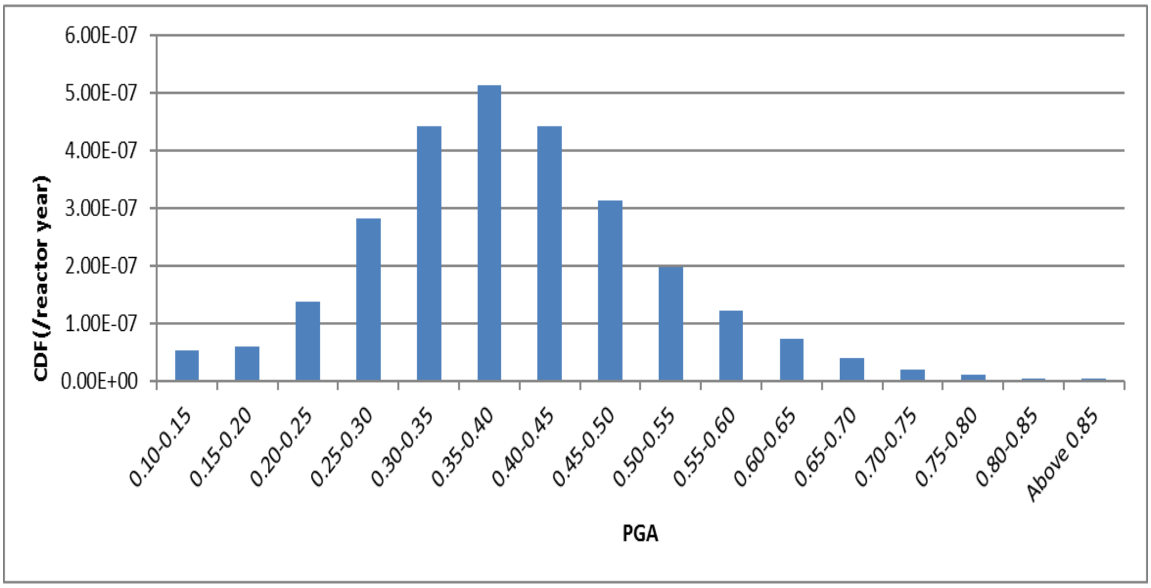

Fig. 4 CDF of PGA intervals.

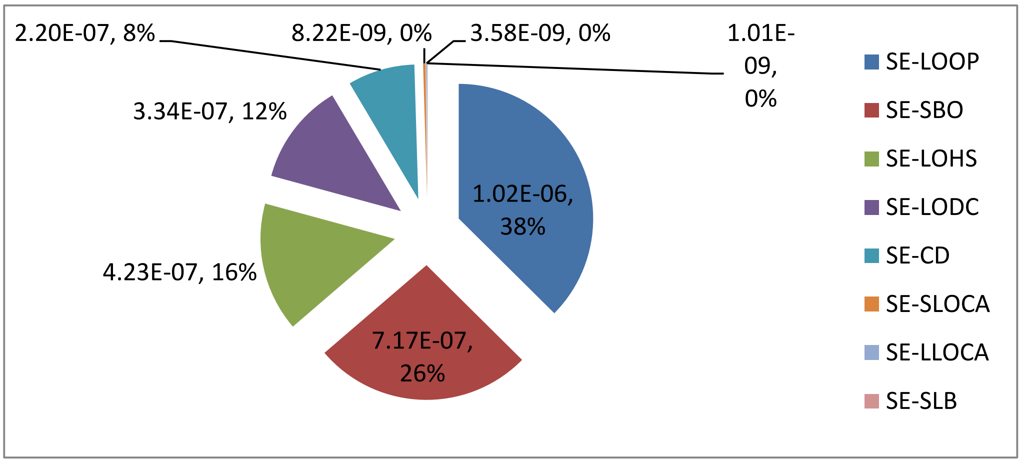

Fig. 5 Pie chart for initiating events category.

5.1.2 Importance of equipment seismic failure

According to the seismic overall risk consequence, we have specific-plant importance analysis for critical equipment using RiskSpectrum software. Table 3 shows equipment seismic failure importance, including Fussell-Vesely importance of components (FC), Risk Decrease Factor (RDF), Risk Increase Factor (RIF).

According to Table 3, ceiling in main control room, auxiliary feeding water tank, DC power and AC power are the important and sensitive equipment.

Table 1 Equipment Seismic Failure contribution to total CDF

NO.	Equipment ID	Description	FC	RDF	RIF
1	MCR-CEIL-SE	Main control room ceiling	2.25E-01	1.29E+00	2.96E+00
2	MCRFACTOR	Conditional Factor	2.25E-01	1.29E+00	1.20E+00
3	LNE360CR-SE	LNE360CR Switch Box	1.50E-01	1.18E+00	3.56E+00
4	ASG001BA-SE	Auxiliary feeding water tank	9.10E-02	1.10E+00	6.99E+00
5	LBA001TB-SE	110V、48V DC Power	5.92E-02	1.06E+00	3.09E+00
6	LHB001TB-SE	B train 6.6Kv AC Power	5.34E-02	1.06E+00	1.78E+00
7	LHQ900AP-SE	B train Diesel Generator	5.30E-02	1.06E+00	1.67E+00
8	LLB001TB-SE	B train 380V AC Power	5.25E-02	1.06E+00	2.77E+00
9	LHP900AP-SE	A train Emergency Diesel Generator	4.72E-02	1.05E+00	1.61E+00
10	LHQ401AR-SE	B train Emergency Diesel Generator Cabinet	4.66E-02	1.05E+00	1.81E+00

5.2 Sensitivity analysis

Sensitivity analysis is to identify the sensitive equipment and human errors during calculating CDF, the modeling assumptions, success criteria and data sensitivity which have the potential significant influence on the results, including initiating events, basic events, human errors, reliability parameters. The following sensitivity analysis is respectively carried out according to the current assumptions.

5.2.1 Sensitivity analysis case1

Sensitivity analysis is done for intervals selecting of ground motion acceleration. The traditional way is the average section, usually around 8 segments. But now the method is usually more than 12 pieces. Figure 6 gives CDF histogram of 6 segments PGA interval. Table 4 gives the respective contribution of 6th and 16thacceleration interval.

By analysis for case1, the thinner the acceleration intervals divide, the smaller the CDF value is. Interval division from 6 to 16, the CDF contribution is reduced by 14.42%. Visibly, thinner intervals make the results more accurate. Evaluation results of 6 intervals division will be relatively conservative, and 16 intervals division is more accurate. And more and more thin interval, the results will become more reasonable and accurate, but it will bring us the huge workload. Therefore the balance between the above should be considered during the risk analysis.

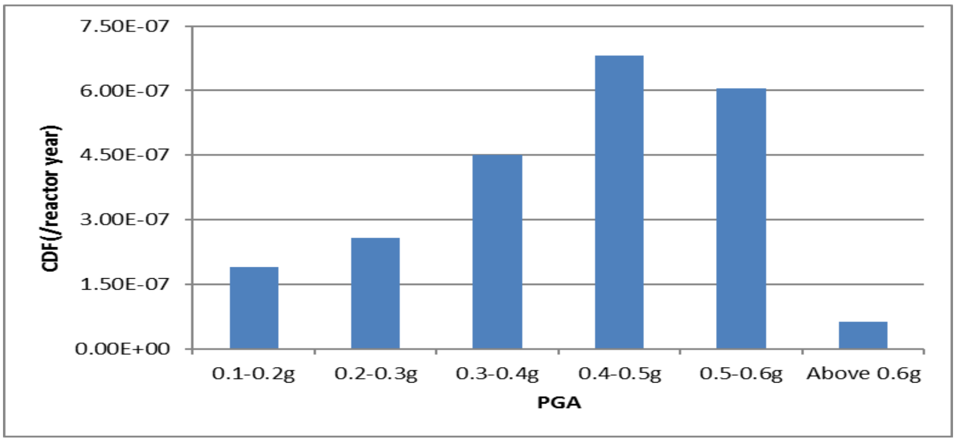

Fig. 6 CDF of PGA intervals.

Table 2 Sensitivity analysis case 1

Comparative item	PGA 6	PGA 16
CDF(/reactor year)	3.19E-6	2.73E-6
Contributions interval	SE3/SE4/SE5	SE5/SE6/SE7
interval value	0.3~0.6g	0.3~0.55g

5.2.2 Sensitivity analysis case 2

This paper considers main control room panels' failure and ceiling failure, which may influence the human actions. If the main control room panels failure, the human actions fail inevitably. If the ceiling fails, the situation is different, the influence needs to be modeled as a human event; two kinds of assumptions are taken into account in fault tree model. One assumption is that the human actions have 50% conditional failure under the ceiling failure; another assumption is 10% conditional failure. Table 5 shows the respective contribution of ceiling failure influence under the two assumptions.

Table 3 Sensitivity analysis case 2

Assumptions	Ceiling failure influence	
Conditional factor	0.5	0.1
CDF(/reactor year)	2.73E-6	2.0E-6

Through the analysis for case 2, CDF contribution for the second assumption reduced by 26.73%. Visibly, the assumptions cause PSA contribution significant to the seismic PSA. From the results of the tables, the ceiling failure is sensitive to the seismic CDF. However, the ceiling failure has a lot of uncertainty, it is difficult to quantify. Maybe it is a good way to give a different conditional failure value under different peak ground acceleration.

6 Conclusions

Through the seismic PSA analysis, we can identify the weakness of the system, equipment, design or installation, equipment defects, and find important human actions, and help nuclear power plants improve the design, and raise the ability and safety level of plants response to disasters.

According to mega-kilowatt nuclear power plant seismic risk analysis results, there is a lot of uncertainty for disasters PSA methods and parameters selection; therefore, it is important to develop sensitivity analysis and find the important item, According to the above comparison and analysis, the results can be seen as followed:

1) Under the SSE PGA earthquake, CDF is less than 2E-07/ reactor*year. The proportion is very small. Nuclear power plants safety under SSE is high. The real high PGA earthquakes' contribution to the overall risk level is not large. CDF contribution from the ground motion acceleration range between 0.3g~ 0.45g is the most significant.

2) The earthquake risk contribution of 16 PGA intervals and 6 PGA integrals in Table 5-3 should be paid attention. More and thinner interval, the results will become more reasonable and accurate.

3) According to the above results, because of the low fragility for the electrical equipment and the

redundancy AC&DC power systems common cause failure, it can be seen that Loss of off-site power and Loss of emergency AC power caused by earthquake are the highest. The two categories accidents make 60% contributions to the total risk.

4) This paper analyzes a specific mega-kilowatt nuclear power plant's safety shutdown, its contributors include ceiling in MCR, ASG tank, DC power and AC power. And the ceiling failure has a lot of uncertainty; it is sensitive to the seismic CDF.

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