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Development and Implementation of Seismic Human Reliability Analysis in Japan

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Abstract:
The impact of a seismic event on the performance of operators is one important element in the development of a modern seismic PRA and significant focus has been dedicated to this topic in the most recent seismic PRAs developed in light of the Fukushima Daiichi accident. Seismic impact on Human Reliability Analysis (HRA) is currently one of the key topics for the upgrade of seismic PRAs underway in Japan.

Historically, seismic PRAs developed in Japan addressed the impact on human reliability analysis in a less detailed way. With the availability of the EPRI method, which is widely used seismic HRA method in the U.S., it is desirable to conduct a in-depth evaluation using EPRI method to identify challenges in its application.

This paper presents insights from the development and implementation of seismic HRA in Japan. Case study using data and models of actual plant in Japan is conducted and plant specific damage state bin in Japan is discussed in detail. In addition, pilot evaluation of screening quantification using plant specific damage state bin in Japan is conducted. A significant focus is given to implementation of the EPRI method to an actual plant in Japan, considering Japanese conditions including relatively large seismic hazard level at the site.

Keywords: PRA, HRA, Seismic.

1. INTRODUCTION

The impact of a seismic event on the performance of operators is one important element in the development of a modern seismic PRA and significant focus has been dedicated to this topic in the most recent seismic PRAs developed in light of the Fukushima Daiichi accident. Seismic impact on Human Reliability Analysis (HRA) is currently one of the key topics for the upgrade of seismic PRAs underway in Japan.

The effects of the earthquake on components and instrumentation may adversely affect the performance of plant operator during the resulting severe plant conditions. These effects must therefore be considered when evaluating failure probability of operator actions in response to seismic events.

A widely used seismic HRA method in the U.S. is provided in EPRI 3002008093, "An Approach to Human Reliability Analysis for External Events with a Focus on Seismic [1]." This method provides seismic-specific guidance for consideration of above effect including relevant performance shaping factors (PSFs) based on operational experience and existing research and provides a general screening approach and then guidance on a more detailed quantification method that can be applied to seismic events. The implementation of the method still relies on plant-specific consideration related to system and fragility analysis that are left to the judgement of the analyst.

Historically, seismic PRAs developed in Japan addressed the impact on human reliability analysis in a less detailed way. For example, in some cases, multiplier is applied to the Human Error Probabilities (HEPs) of internal event PRA to calculate seismic HEPs, taking the stress factor into account but assuming the constant HEPs independent from seismic motion. With the availability of the EPRI method, it is desirable to conduct a in-depth evaluation using the seismic HRA method described in EPRI guidance to identify challenges in its application.

This paper presents insights from the development and implementation of seismic HRA in Japan. A significant focus is given to implementation of the EPRI method to an actual plant in Japan, considering Japanese conditions including relatively large seismic hazard level at the site.

2. EVALUATION PROCESS

An overview of the summarized evaluation process described in the EPRI guidance is shown in Figure 1. This process initially identifies and defines the Human Failure Events (HFEs) to be modeled in the seismic PRA and confirms their feasibility. It also defines damage state bin required by both the screening quantification method and the detailed quantification method. In the seismic PRA, seismic hazards are split into bins so SSC failure probabilities can be calculated across the spectrum of the hazard ("hazard bins"). Damage state bins are distinct from hazard bins in that they define the break points at which the underlying context of the action changes substantially enough to impact the reliability of the action. etc.

Next, screenings quantification is performed using the screening tree shown in "Curtiss-Wright/Scientech Seismic HRA Insights and Lessons Learned from the Application of EPRI Report TR-1025294" [2]. The factors including action location, damage state, time margin, etc. need to be considered. These factors are used to determine the screening HEP or multiplier to be applied to the Human Error Probabilities (HEPs) evaluated in the internal event PRA. Detailed quantification of HEPs for the seismic PRA is done for HFEs that are shown to be risk significant to the model following initial quantification with the screening quantification. For these HFEs, detailed analysis is performed for each plant-defined damage state bin. Finally, the impact of seismic events on operator performance is evaluated by incorporating the HEPs calculated by screening quantification or detailed quantification into the model.

Of this process, this paper focuses on the damage state definition and screening quantification. Case study using data and models of actual plant in Japan is conducted and plant specific damage state bin in Japan is discussed in detail. In addition, pilot evaluation of screening quantification using plant specific damage state bin in Japan is conducted. The results of the case study of the damage state bin considering the Japanese conditions are shown in Section 3, and the results of the pilot evaluation of screening quantification based on the damage state bin set in Section 3 are shown in Section 4.

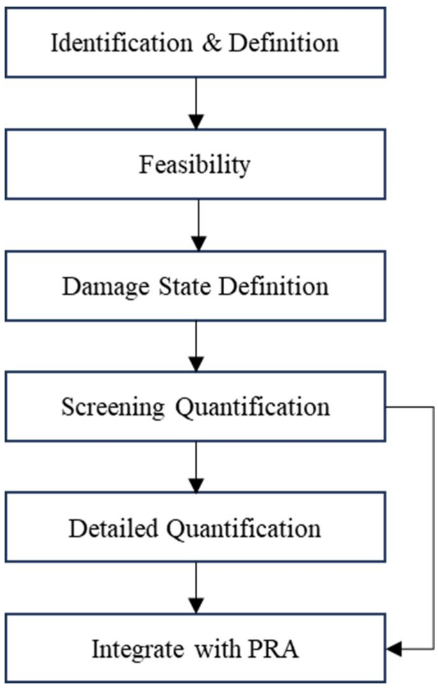

Figure 1. Summarized Evaluation Process

3. DAMAGE STATE BIN CONSIDERATION

3.1. Damage State Definition

In the seismic PRA, seismic hazards are split into bins so SSC failure probabilities can be calculated across the spectrum of the hazard (“hazard bins”). Damage state bins are distinct from hazard bins in that they define the break points at which the underlying context of the action changes substantially enough to impact the reliability of the action. The definition of hazard bins and their number and size (i.e., hazard span) is normally driven by quantification optimization. HRA damage states, on the other hand, are defined by grouping the plant SSCs by their level of expected impact on human performance if they fail (e.g., increased general workload, more difficult cognition, more challenging working environment, etc.). For quantification purposes, the HRA damage bins need to align with the seismic hazard bins. Thus, the damage state bins provide the map between the human performance drivers or PSFs and the hazard bins, which represent levels of damage to the plant SSCs.

For screening, generic damage states for HRA have been qualitatively defined in EPRI guidance. Because the design basis for the range of seismic events can vary substantially from plant to plant, the bins selected in EPRI guidance reflect the effect of the seismic event on the plant rather than providing absolute values (e.g., PGA values). There are some examples of mapping seismic ground motion bins into the generic damage state bins based on the plant-specific SSC fragilities in EPRI guidance, but these examples cannot be applied generically.

3.2. Consideration of Damage State Bins in Japan

Considering the conditions in Japan, it is difficult to define the damage state bin only based on the definitions and examples in the EPRI guidance. For example, in many cases, the EPRI guidance sets seismic motion smaller than plant Safe Shutdown Earthquake (SSE) as Bin1. In Japan, however, the plant SSE is large enough that seismic motion of this level would result in loss of offsite power, and the damage condition is different from that in the U.S. In developing a seismic HRA methodology applicable to Japan, it is necessary to define damage state bins based on the results of seismic motion and fragility evaluation for individual plants in Japan.

In order to define a damage state bins applicable to Japan, the Conditional Core Damage Probability (CCDP) is a good indicator to consider the impact of the failure of the components due to their fragilities. Figure 2 shows the frequency of earthquake, Core Damage Frequency (CDF), and Conditional Core Damage Probability (CCDP) as a function of seismic motion when the seismic HEP is maintained unchanged to internal event PRA HEP. As can be seen, in the range of seismic motion from about 0.4G to 1.8G, CCDP increases up to 1.0. This means that many SSCs lose their functions in this area of seismic motion. It is necessary to set the damage state bins appropriately with reference to these curves.

Furthermore, in order to simultaneously confirm the damage state according to seismic motion, the plant-specific SSC fragilities (HCLPF) for major components were added to Figure 2. As can be seen, Loss of offsite power (LOPA) occurs with relatively small seismic motion, and the loss of seismic Class B piping occurs at approximately 0.5G, major safety systems from 0.8G through 1.4G, instrumentation at around 1.4G, and major buildings from 1.5G through 1.8G.

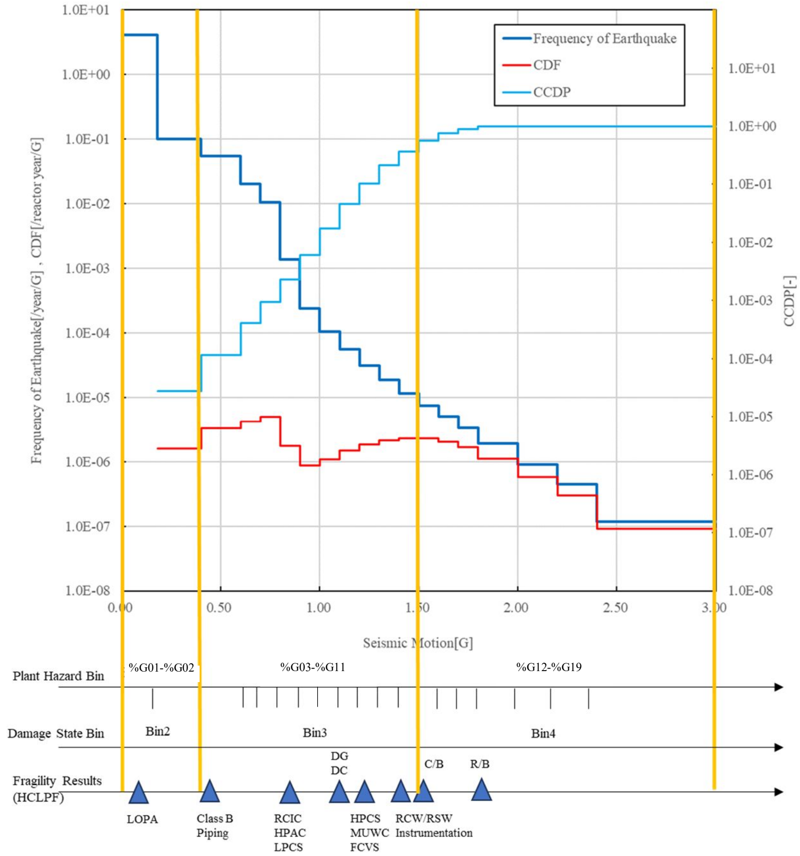

Figure 2. CCDP Plots with Fragility Results

Table 1. Candidate of Damage State Bins for Japanese Specific Plant

Bin	Damage State Description	Plant Hazard Bins		Plant Specific Criteria Used	Fragility Results (HCLPF)
		Bin	PGA Range (G)		
1	No expected damage to safety and non-safety related SSCs	NA	NA	Not used	NA
2	No expected damage to safety-related SSCs or to rugged industrial type non-safety SSCs. Damage may be expected to unimportant non-safety SSCs and to switchyard.	1	0.00-0.18	Start to experience failure of non-safety SSCs important to plant operation and switchyard (LOPA expected).	LOPA (0.10)
		2	0.18-0.40		
3	Widespread damage expected to non-safety related SSCs and/or some damage expected to safety related SSCs. Lots of alarms and vibration trips.	3	0.40-0.60	Experience damage to most of the safety related SSCs.	Seismic Class B piping (0.46)
		4	0.60-0.70		
		5	0.70-0.80		
		6	0.80-0.90		
		7	0.90-1.00		
		8	1.00-1.10		
		9	1.10-1.20		
		10	1.20-1.30		
		11	1.30-1.40		
4	Substantial damage to safety related and non-safety related SSCs.	12	1.40-1.50	Experience significant damage to instrumentation and safety-related buildings.	Instrumentation (1.42)
		13	1.50-1.60		
		14	1.60-1.70		
		15	1.70-1.80		
		16	1.80-2.00		
		17	2.00-2.20		
		18	2.20-2.40		
		19	2.40-3.00		

The selection of the breaking points for damage state bin is left to the judgement of the analyst, based on insights from the fragility of the plant and of individual components. Therefore, there are many possible definitions, but one candidate for the definition of damage state bins for specific plant in Japan is shown in Table 1. This definition was determined primarily based on the ERPI Guidance definition and the plant-specific SSC fragilities (HCLPF) for major components shown in Table 1, although the CCDP plot was used as a reference. The following is the explanation and discussion for each bin.

- Damage State Bin 1 is defined as "No expected damage to safety and non-safety related SSCs" in the EPRI guidance. Since even the plant hazard bin at the smallest seismic motion would cause a LOPA in the specific plant, it was decided not to use this damage state bin since there is no plant hazard bin that corresponds to the definition.
- Damage State Bin 2 is defined as "No expected damage to safety-related SSCs or to rugged industrial type non-safety SSCs. Damage may be expected to unimportant non-safety SSCs and to switchyard." in the EPRI guidance. For the subject plant, Damage State Bin 2 is defined as 0.00G-0.40G, where non-safety SSCs affecting plant operation and switchyards begin to lose function. This corresponds to Plant Hazard Bins 1-2. The fragility results for Damage State Bin 2 shows that some of the non-safety systems failed and LOPA occurred, which is consistent with the EPRI guidance definition.
- Damage State Bin3 is defined as "Widespread damage expected to non-safety related SSCs and/or some damage expected to safety related SSCs. Lots of alarms and vibration trips." in the EPRI guidance. For the subject plant, Damage State Bin 3 was defined as 0.40G-1.50G, where experience damage to most of the safety related SSCs and instrumentation. This corresponds to Plant Hazard Bins 3-12. The fragility results for Damage State Bin 3 shows that most of the safety systems and instrumentation are failed, which is consistent with the EPRI guidance definition.
- Damage State Bin 4 is defined as "Substantial damage to safety related and non-safety related SSCs." in the EPRI guidance. For the subject plant, Damage State Bin 4 is defined as 1.50G-3.00G, where experience significant damage to safety-related buildings. This corresponds to Plant Hazard Bins 13-19, and the fragility results for Damage State Bin 4 shows that safety-related buildings such as R/Bs and C/Bs have lost their functionality, which is consistent with the EPRI guidance definition.

This candidate of the definition is determined to meet the damage state bin definition in EPRI guidance. However, in this case, all the seismic motion range where CCDP is significantly changing have been included in one bin, i.e., Bin3. Therefore, there is a possibility that this bin needs to be divided and further study is required. In the future, the candidates of the definition need to be considered in more detail based on the information how much CDF changes with these candidates. If the change is minimal, it may show that sensitivity on binning breaking points is minimal, which helps the analyst to make the decision.

4. SCREENING QUANTIFICATION

A pilot evaluation of screening quantification was conducted using a damage state bin defined in Section 3. First, the HFEs modeled in the seismic PRA model at the actual plant in Japan were confirmed, and the HFEs to be evaluated for the seismic HRA were selected.

In developing a seismic HRA methodology, one important factor to consider is how much the seismic HEPs evaluated using the developed methodology affects the CDF. One indicator to confirm this is the RAW importance, which indicates how much the CDF increases when the probability of occurrence of the event in question is set to 1.0. In the screening quantification, the seismic HEPs are set at 1.0, 50 times the HEPs of internal event PRA, or etc. using the screening tree. Consequently, the seismic HEPs would be significantly larger than the HEPs of internal event PRA. Therefore, the RAW importance can be set as an indicator to see the impact on the CDF due to such significant large HEPs.

The seismic PRA model of actual plant in Japan was used to calculate RAW importance and the HFEs that appear at the top of the RAW importance were considered. As a results, one HFE was selected for the seismic HRA pilot evaluation: failure to change High Pressure Core Spray Systems (HPCS) water source. This is an operator action to switch the water source for HPCS from Suppression Pool (S/P) to Condensate Storage Tank (CST) which is necessary for the decay heat removal and are important operator action in the seismic PRA.
Screening quantification was conducted for the selected HFE. In the screening quantification, seismic HEPs were calculated using the Screening Tree shown in EPRI guidance, with information such as action location,

damage state, time margin, etc. as inputs. Among these, for the damage state bins, the bins defined in Section 3 was used.

The results of each branch of the screening tree are shown in Table 2. Since this operator action is performed when the water temperature of S/P reaches 80°C and is not an initial response, "No" is selected for "Immediate Memorized Action". Since this action is performed in the control room, select "Control Room" for "Action Location. For the damage status, set Bin 2 through Bin 4 according to Table 1 defined in Section 3. "Time Margin" is set to ">30min" since considering timeline of this action in the IEPRA, time margin is about 2 hours and this value is large enough even considering the increase of Tdelay, Tcog, and Texe due to the earthquake. Also, time margin is large enough and it is likely that the damage state of the plant is known when this action is performed, "Cue After Damage State" is set to "Yes".

Table 2. Screening Tree Results for Pilot Evaluation

Screening Tree Branch	Screening Tree Result
Immediate Memorized Action	No
Action Location	Control Room
Damage State	See Table 1
Time Margin	> 30min
Cue After Damage State	Yes

Table 3. Screening Quantification Results for Pilot Evaluation

HFE/Bin	Screening Quantification Result	HEP
IEPRA HFE	-	3.5E-03
Seismic HFE (Bin2)	IEPRA HEP	3.5E-03
Seismic HFE (Bin3)	IEPRA HEP×5	1.7E-02
Seismic HFE (Bin4)	IEPRA HEP×30	1.0E-01

The screening HEPs calculated according to the branches shown in Table 2 are summarized in Table 3. The results of the pilot evaluation showed that for the selected HFE, the seismic HEP was the same as the IEPRA HEP for Bin2, the seismic HEP was 5 times higher than the IEPRA HEP for Bin3, and the seismic HEP was 30 times higher than the IEPRA HEP for Bin4. In particular, the seismic HEP was large enough to be around 0.1 for Bin4, which is close to the screening HEP value. Thus, when an evaluation based on the EPRI guidance is performed, the seismic HEP increases with seismic motion, indicating that larger seismic motion has a significant impact on operator performance. Since the constant HEPs independent from seismic motion was assumed in some cases in Japan when developing seismic PRAs, this pilot evaluation showed that it is important to conduct the evaluation according to the seismic motion based on the EPRI guidance. Since this study was limited to the screening approach, we need to implement the detailed approach to compare the results of screening quantification and detailed quantification in the future.

5. CONCLUSION

The insights from the development and implementation of seismic HRA in Japan was discussed. The case study using data and models of actual plant in Japan was conducted and plant specific damage state bin in Japan was discussed. The selection of the breaking points for damage state bin is left to the judgement of the analyst, based on insights from the fragility of the plant and of individual components. In the future, the candidates of the definition for plant specific damage state bin in Japan need to be considered in more detail based on the information how much CDF changes with these candidates.

In addition, pilot evaluation of screening quantification using plant specific damage state bin in Japan was conducted. The results showed that the seismic HEP increased with seismic motion, indicating that larger seismic motion has a significant impact on operator performance. Since the constant HEPs independent from seismic motion was assumed in some cases in Japan when developing seismic PRAs, this pilot evaluation showed that it is important to conduct the quantification according to the seismic motion based on EPRI guidance. Since this study was limited to the screening approach, we need to implement the detailed approach to compare the results of screening quantification and detailed quantification in the future.

References

[1] EPRI, An Approach to Human Reliability Analysis for External Events with a Focus on Seismic, 3002008093, Final Report, December 2016

[2] Michael Hirt, Kaydee Kohlhepp-Gunter, Jan Grobbelaar, Jeff Julius, and Steve Eide, "Curtiss-Wright/Scientech Seismic HRA Insights and Lessons Learned from the Application of EPRI Report TR-1025294", PSAM13, 2-7 October, 2016, Korea