Proposal of an evaluation framework for seismic level 1 multi-unit PRA

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Abstract: The Fukushima Daiichi Nuclear Power Plant was struck by earthquakes and tsunamis in 2011, following the Tohoku Earthquake off the Pacific coast, resulting in core damage to three reactors. This event has attracted significant attention to the risk of external hazards at a site with multiple units. However, there is still little international experience in multi-unit probabilistic risk assessment (MUPRA) to assess a site risk, and methodology for MUPRA is currently under research and no consensus methodology is currently available. In seismic level 1 MUPRA, it is important to consider multi-unit events and inter-unit interactions, such as simultaneous occurrences of seismic-induced initiating events, loss of function of shared equipment, competition for resources and equipment, and human behavior under a multi-unit accident. We have been developing methodologies for level 1 MUPRA. In our study on internal event level 1 MUPRA, we have developed a method for common-cause failures among inter-unit structures and systems and components (SSCs), a method for screening and evaluating human error probability under a multi-unit accident, and a procedure for constructing a multi-unit accident sequence model that can consider inter-unit interactions considering the plant conditions of other units. In addition, in our study on seismic MUPRA, we are developing a method for evaluating joint failure probability among inter-unit SSCs considering correlations of responses and correlations of capacities, and have developed a method of seismic-induced multi-unit initiating event evaluation. In this paper, we propose a practical framework for seismic level 1 MUPRA, based on frameworks of the conventional seismic level 1 single-unit PRA and the internal level 1 MUPRA, that ensures a good balance between implementation cost and accuracy

Keywords: Probabilistic risk assessment, Multi-unit PRA, Seismic MUPRA,

1. INTRODUCTION

In 2011 off the Pacific coast of the Tohoku Earthquake, the Fukushima Daiichi Nuclear Power Plant (1F) was struck by earthquakes and tsunamis, resulting in core damage to three reactors. In this accident, multi-unit (MU) events and inter-unit interactions were observed in the accident progressions such as simultaneous occurrences of seismic-induced initiating events, loss of function of mobile equipment, competition for resources and equipment, and human behavior under a MU accident. Those MU events and inter-unit interactions made accident mitigation more difficult. 1F accident attracted significant attention to the risk of external hazards at a site with multiple units. Since then, discussions of safety goals and site risks [1], and research and developments of MUPRA methodologies have been promoted internationally at various institutions [2].

External hazards such as earthquakes and tsunamis can cause damage to multiple structures, systems, and components (SSCs) in multiple units simultaneously, so one needs to pay attention to the risks from external hazards in a MU site. In Japan, external hazards, especially seismic events, are considered important. Several studies have been conducted for seismic MUPRA: a proposal of a Monte Carlo method for site risk calculation based on seismic single-unit (SU) PRA by Hakata [3], a case study in the MUPSA project of the IAEA [4], and a method for evaluating seismic multi-unit risk based on the logical product of risk-significant accident sequences in seismic SUPRA by Ebisawa et al [5].

The authors have been developing methodologies for a level 1 MUPRA. In the studies on internal event level 1 MUPRA [6], the authors have developed a framework for internal event level 1 MUPRA by extending the existing internal level 1 SUPRA. The developed framework balances the cost and accuracy of the assessment. The authors have also developed the following MUPRA-specific methods for evaluation: a method for common cause failures among SSCs of different units, a method for screening and evaluating human error probabilities (HEPs) under MU accidents, and a procedure for constructing a multi-unit accident sequence (MU-AS) model that can consider MU events and inter-unit interactions considering on plant conditions in other units. In addition, in our study on seismic MUPRA, we have developed a procedure for evaluating seismic-induced multi-unit initiating events (SI-MUIE) [7]. We also have studies methods for evaluating joint failure probabilities [8].

This paper proposes a framework for seismic level 1 MUPRA, extending the framework of internal event level 1 MUPRA and based on seismic level 1 SUPRA. The framework is established based on the assumption that there are no significant interactions among units for neutronic and thermal-hydraulic phenomena even under MU accidents and inter-unit interactions affect accident mitigation equipment and human activities. Section 2 outlines the basic policy for the development of seismic MUPRA methodology, and Section 3 presents the framework for seismic level 1 MUPRA.

2. A BASIC POLICY FOR SEISMIC MULTI-UNIT PRA METHODOLOGY

Seismic SUPRAs have already been conducted widely in Japan, and lots of knowledge and experiment data to support performing seismic PRA are available. In addition, utilizations of risk insights from seismic SUPRA are also being promoted in the safety improvement assessments.

Under such circumstances, seismic MUPRA needs to be cost-effective and provide insights that are not available in SUPRA. To achieve these needs, seismic MUPRA should meet the following requirements:

Requirement (1): Ensure consistency with SUPRA such as model assumptions and the level of detail.
Requirement (2): Conform to conventional SUPRA methods as much as possible.
Requirement (3): Consider MU events and inter-unit interactions in accordance with plant conditions and accident scenarios of other units.
Requirement (4): Provide various risk metrics and risk information.

The intent of Requirements (1) and (2) is to reduce costs and make it easy to conduct seismic MUPRAs. Therefore, a framework of seismic MUPRA follows that of the conventional seismic SUPRA. For example, as a fundamental part of the seismic SURPA framework, risk metrics such as core damage frequency (CDF) for seismic PRA are obtained using the concept presented in Equation (1). The equation applies to MUPRA.

$$\mathrm{CDF} = \sum_i \left[h(\mathrm{bin}_i) \cdot \sum_j \left\{ IE_j(\mathrm{bin}_i) \cdot \sum_k Q_{IE_j,k}(\mathrm{bin}_i) \right\} \right] \quad (1)$$

where, bin_i is the ith bin of seismic acceleration at control point (CP) common to subject units, $h(\mathrm{bin}_i)$ is the seismic event frequency in bin_i, $IE_j(\mathrm{bin}_i)$ is the conditional probability of jth initiating event in bin_i, and $Q_{IE_j,k}(\mathrm{bin}_i)$ is the conditional probability of kth accident sequence of the jth initiating event in bin_i.

The intent of Requirement (3) is to address the importance of MU events and inter-unit interactions to conduct a seismic MUPRA with realistic.

The authors proposed a method to construct an MU-AS model considering the other units' accident progress for internal event level 1 MUPRA (Figure 1) and adopt this method for seismic MUPRA. First, seismic SUPRA models are modified for MUPRA (See Task (c) in Section 3 and [6] for more information). Then exhaustively combining accident sequences for each SUPRA model generates MU-AS candidates. At this point, generated MU-ASs are candidates because some of the candidates are logically invalid due to the effects of MU events and inter. Thus, for each MU-AS candidate, the logical validity of the sequence is examined considering the status of shared equipment, priority use, etc.

The intention of explicitly setting Requirement (4) is to pay attention to note that MUPRA can define various risk metrics, in contrast to SUPRA. For example, [4] lists the following three MUPRA risk metrics related to CDF.

- SUCDF (Single Unit Core Damage Frequency): Frequency of only one unit suffering core damage at a site with multiple units.

- MUCDF (Multiple Unit Core Damage Frequency): Frequency of two or more units suffering core damage at a site.
- SCDF (Site Core Damage Frequency): Frequency of one or more units suffering core damage at a site.

It is essential that a seismic MUPRA model can estimate all the risk metrics and obtain risk information, as each of them provides different perspectives.

Since building a MUPRA model for each of these risk metrics is complicated, the proposed framework estimates risk metrics by summing up MU-AS frequencies, which are quantified individually, according to the definition of each risk metric, instead of building MUPRA models according to risk metrics.

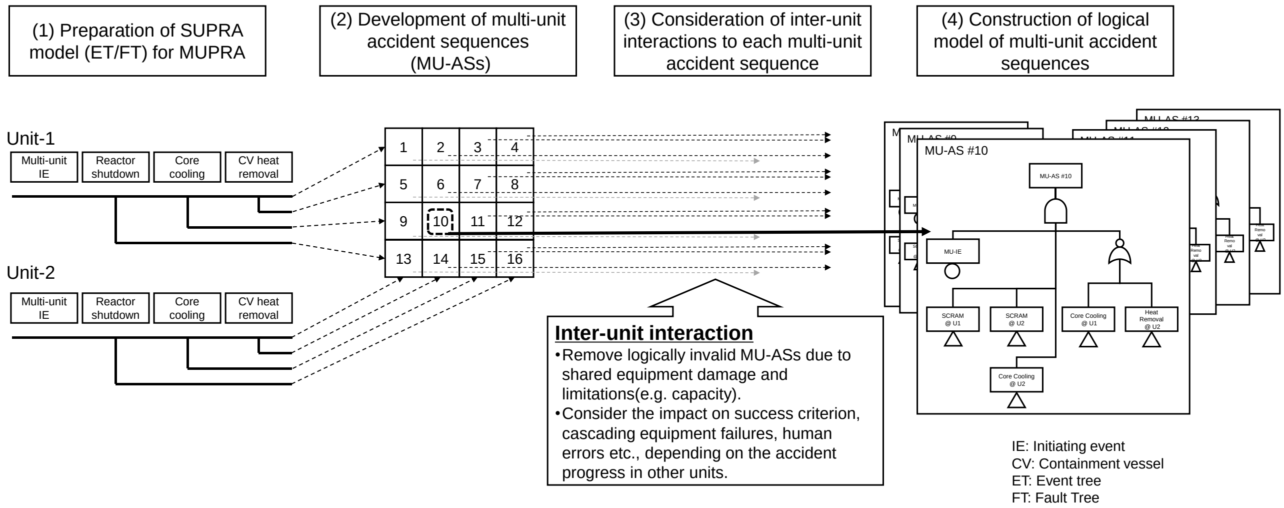

Figure 1 Schematic image of constructing multi-unit accident sequence model [6]

2.1 Multi-unit events and inter-unit interactions considered in seismic MUPRA

The proposed seismic MUPRA method first requires identifying accident scenarios and events to be evaluated, as well as inter-unit interactions among units. Since the proposed seismic MUPRA method is based on the concept of expanding SUPRA, it is important to identify MU events and inter-unit interactions, which are not included in SUPRA and may cause MU-specific scenarios. However, international experiences of MUPRA are still limited and scenarios to be considered in MUPRA have not been widely recognized as common knowledge. Therefore, this section summarizes the MU-specific events, scenarios, and contexts to be considered in MUPRA based on previous research that has analysed MU incidents and accidents such as: Muhlheim et al.'s analysis to examine multi-unit initiating events (MUIEs) for small modular reactors [9]; Kenneth et al.'s proposal for a framework to assess site integration risk and identify inherent vulnerabilities due to inter-unit interactions during accidents [10]; Schroer et al.'s analysis of U.S. nuclear power plant's Licensee Event Reports (LERs) recorded from 2000 to 2011 [11]. The authors also analysed the 1F accident and trouble information of Japanese nuclear power plants recorded in NUClear Information Archives (NUCIA).

Based on this information, the MU events and interactions to be considered in seismic level 1 MUPRA are identified as follows.

(a) Loss of functionality of shared SSCs due to random events and seismic events
(b) Occupation of shared SSCs and resource
(c) Support to other units (e.g. power interchange)
(d) Joint failure of SSCs among units due to an earthquake (responses/capacities correlation)
(e) Cascading events across units
(f) Common-cause failure of inter-unit SSCs due to internal factor
(g) Impact of accident situation in other units on human actions and organizational response, and dependency inter-unit human action

Events related to equipment or human actions common among units are modelled by assigning the same IDs to their basic events so that minimal cutsets are properly handled These events mainly include (a) and (g).

For events related to resource occupation or support of other units, logical validities of the MU-ASs are checked by organizing the conditions under which the events occur, and invalid MU-ASs are excluded from the evaluation These events mainly include (b) and (c).

For events with inter-unit dependencies, such as inter-unit CCF, joint failure due to an earthquake, and dependent human actions among different units, co-occurrence probabilities of events with dependencies are estimated according to the degrees of commonality or correlation taking into account intra-unit and inter-unit differences, and basic events representing the co-occurrence are modelled or the probabilities for conjunctions of events with dependencies are corrected in sequence quantification. These events mainly include (d) and (f).

For events with causal relationships, such as cascading events across units or increased psychological stress due to accident conditions in other units, modelling approaches depend on the affecting area of the event. If such events affect a few failures of SSCs and human actions, and the probabilities of them, the occurrence probabilities are corrected. If such events affect wide plant response and result in new accident scenarios, new MU-ASs are developed for such scenarios. These events mainly include (d) and (e).

Detailed descriptions of the specific modelling methods and examples of models for (a), (b), (c), (e), (f), and (g) for internal event level 1 MUPRA can be found in the authors' previous studies [6,7,12].

2.2 Requirements for seismic SUPRA models to be used in seismic MUPRA

The proposed seismic MUPRA method focuses on the impacts of MU events and inter-unit interactions limited to the availability of mitigation measures because it is unrealistic that neutronic phenomena in core and thermal-hydraulic behavior in the coolant, containment vessel, etc. would affect those of other units. Then the approach taken in the internal event level 1 MUPRA [6] is principally applicable, and seismic SUPRA models for a seismic MUPRA should also meet the following requirements.

Requirement 0: Seismic SUPRA models with sufficient quality and scope are available.
In the seismic MUPRA framework presented in this paper, a seismic MUPRA model is developed and evaluated by adding contexts of MU accidents, such as MU events and inter-unit interactions, to seismic SUPRA models. Therefore, seismic SUPRA models must cover the hazards and events included in the scope of seismic MUPRA, and they must be of the same or higher quality than that required to obtain the desired risk information from seismic MUPRA.

Requirement 1: Basic events have a unit identifier (or common identifier).
There are cases where components in different units have the same component ID. If they have identical basic event IDs, they cannot be distinguished. When performing Boolean operations on the minimal cutsets (MCSs), these basic events are merged in an MCS in accordance with the absorption law of Boolean algebra. Therefore, a unit identifier is required for each basic event ID to distinguish components when their component type, equipment number, and failure mode are identical.

Requirement 2: All mitigation measures credited in seismic MUPRA are modeled.
The proposed MU-AS modeling method is based on the accident sequences developed in seismic SUPRA models. Then, the MU-AS model is constructed by deleting the mitigation measures that are no longer credited owing to inter-unit interactions. Therefore, all the mitigation measures credited in a seismic MUPRA model need to be modeled in SUPRA models.

Requirement 3: ET heading events are arranged in chronological order.
Some inter-unit interactions depend on accident progressions in other units; in other words, they are time-dependent. Therefore, when developing a seismic MUPRA model, it is better for ET heading events to be in chronological order to analyze when inter-unit interactions occur and implement the interactions in the model. However, ET heading events do not have to be in chronological order, if it does not pose a problem and there is a reasonable such as model size reduction or scenario readability.

Requirement 4: Reference control points in hazard and fragility analyses are the same among units.
In seismic MUPRA, as in seismic SUPRAs, CDF is estimated by summing up the conditional core damage probability (CCDP) at a given seismic intensity multiplied by its seismic occurrence frequency. If the hazard curves are not identical among the units and if the units do not have correspondence among hazard curves, it is not possible to form an evaluation seismic intensity axis common to the units, and one cannot conduct seismic MUPRA. Therefore, this paper requires that a reference control point (CP) be the same among units. It should be noted that research to obtain correspondence of hazard intensities among units is underway in the field of seismic hazard evaluation, and the above requirement is not the case when such correspondence is available.

3. FRAMEWORK FOR THE SEISMIC LEVEL 1 MUPRA

Based on the discussion in Section 2 and our experience with internal event level 1 MUPRA, we propose the implementation flowchart for seismic level 1 MUPRA as shown in Figure 2. The implementation chart has mainly 10 tasks from (a) to (j). The outline for each task is described below.

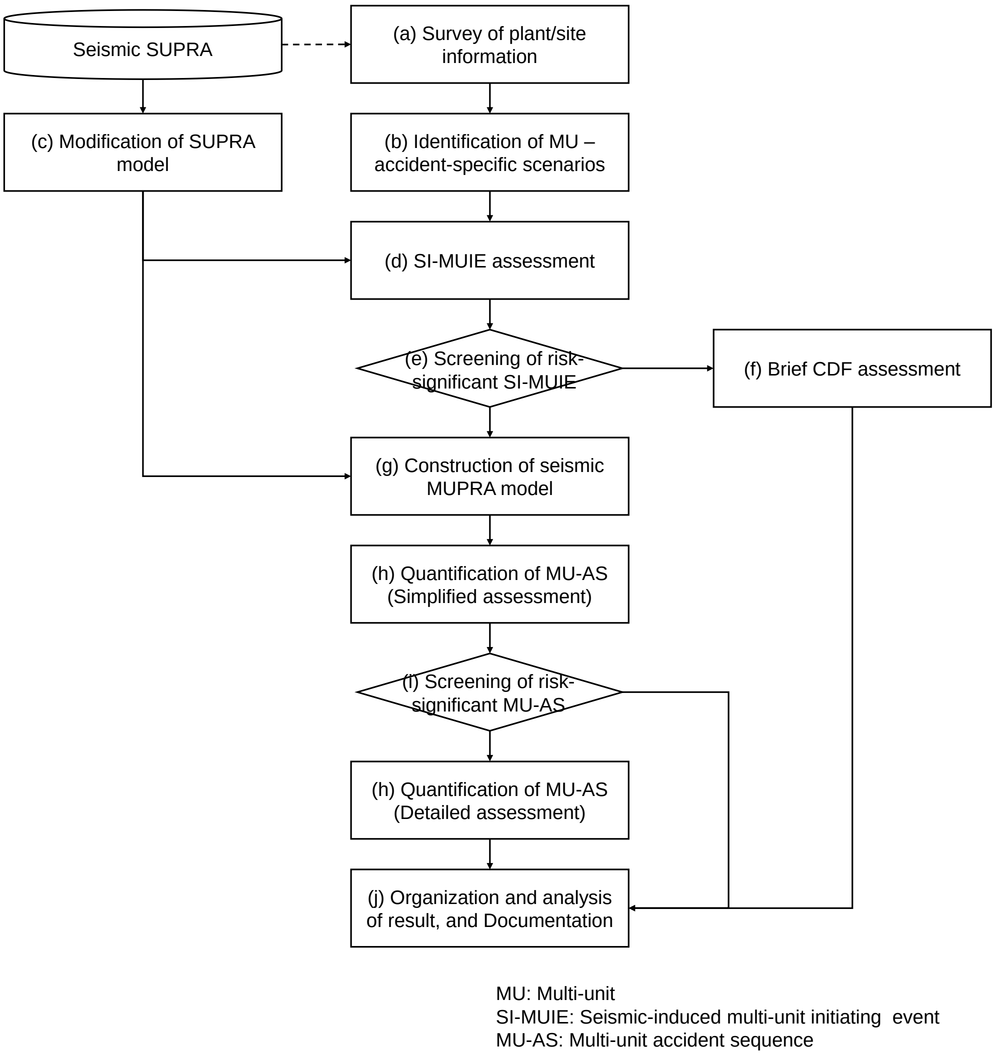

Figure 2 Implementation flowchart of seismic level 1 MUPRA

Task (a): Survey of plant/site information

First, a survey of plant information is conducted in a seismic SUPRA. Atomic Energy Society of Japan (AESJ) seismic PRA standard [2] provides the following items as examples of survey items. The information from these items is also required in a seismic level 1 MUPRA.

- Information on fundamental specifications, configuration of systems and equipment, seismic design features, and plant layout features
- Seismic source characteristics and seismic motion propagation characteristics
- Information related to capacity assessments and response assessments for buildings and equipment.

The following additional information needs to be collected to consider MU events and inter-unit interactions organized in Section 2.1.

- SSCs shared among units.
- SSCs and mitigation measures that can be affected as a result of accident progression in other units.
- Commonalities of SSCs among units (information related to common cause failures and correlations of capacities)
- Mitigation measures sharing resources (equipment, fuel, water sources, personnel, etc.)
- Operating strategies under MU accidents (e.g., rules for prioritizing shared equipment and resources, and providing support to other units)
- Plant layout throughout a site and characteristics (or differences) of ground structures under each unit and commonalities of SSCs among units (information related to response correlations)
- Layout information to identify proximities of buildings, SSCs location, and mitigation action place.

In addition, documents and assessment results (risk profiles and importance analysis, etc.) organized in existing seismic SUPRA and internal event MUPRA are collected for implementation of the later tasks.

Task (b): Identification of MU-accident-specific scenarios

The MU-AS modelling method applied in this paper assumes that all equipment and responses expected for accident mitigations in MU accidents are modelled in seismic SUPRA models provided for a seismic MUPRA. MU-AS models are constructed by exhaustively combining sequences for each seismic SUPRA model and by considering that MU events and inter-unit interactions cause equipment and mitigation responses to become unavailable, success criteria to change, and so on. Therefore, this task identifies scenarios that cannot occur and success criteria different from seismic SUPRAs due to MU events and inter-unit interactions and determines their modelling strategies. The following potential events are checked, and those details such as occurrence condition, related equipment, impact and so on are specified.

- Loss of function of shared equipment
- Priority use of shared equipment and resources
- Supplying power, etc. from/to other units.
- Common-cause failure of inter-unit SSCs (due to random causes)
- Impact of accident conditions in other units on human actions and organizational response, and dependency of tasks in different units
- Cascading failures of SSCs in different units due to spatial proximity
- Simultaneous loss of function of SSCs of different units located in the same building due to damage to the building.
- Propagation to other units of consequential events such as flooding and fire resulting from seismic failure of SSCs.

Task (c): Modification of seismic SUPRA model

This task checks whether seismic SUPRA models provided for a seismic MUPRA meet the four requirements in Section 2.2. If not, this task modifies the seismic SUPRA models to meet the requirements. In addition, SUPRA model sizes are reduced as an optimization for MUPRA model construction. The following are some possible approaches to reduce model sizes.

Remove non-important accident sequences
The seismic SUPRA accident sequences that have almost insignificant impacts on risks can be removed. The following criteria should be used.

- Sequences with low frequencies that are not considered to be risk-significant. It is noted that sequences with low frequency but with significant impact due to the occurrence of the event (i.e., significant impact when considering up to the evaluation of later stages such as level 2 PRA) should not be removed
- Sequences that are not significantly affected by or that do not significantly affect other unit sequences relatively

Condense accident sequences

Heading events that are not related to MU events or inter-unit interactions and whose subsequent accident sequence has a similar expansion are condensed with logical consistency to reduce the number of accident sequences.

Integrate basic events

To reduce system reliability model sizes and the number of minimum cutsets (MCSs), multiple basic events for each failure mode are integrated and modeled as a single basic event. If there are dependencies among the integrated base events, MCSs are quantified by noting the joint failure probabilities of the dependent events.

Since inter-unit interactions are applied at an ET heading level when constructing an MU-AS model, headings of accident sequences with a mixture of shared and unshared equipment are split up as necessary. Finally, it is checked whether the amounts of change in risk metrics due to these model modifications are within acceptable levels.

Task(d): Seismic-induced multi-unit initiating event (SI-MUIE) assessment

This task identifies SI-MUIEs and quantifies their occurrence frequencies considering a co-occurrence of initiating events among units and/or their cascading effects over units. The authors proposed a method for SI-MUIE assessment in [7]. The proposed SI-MUIE quantification process extends the hierarchical event tree method used in conventional seismic SUPRA to seismic MUPRA.

The units of risk metrics in seismic MUPRA as well as in internal event level 1 MUPRA are [/site year], rather than [/reactor year]. Therefore, those of frequency of SI-MUIE are also [/site year].

Task (e): Screening of risk-significant SI-MUIE

In typical seismic SUPRAs in Japan, the number of seismic-induced initiating events (e.g., seismic-induced loss of cooling accident) exceeds 10. The variations of SI-MUIEs are around 100 in the case of 2 units, although they vary depending on the effects of shared equipment failure among units and cascading effects across units.

It is practically difficult to evaluate CDF for all SI-MUIEs in detail due to the large number of their variations. Therefore, this task classifies SI-MUIEs into two categories in terms of significance based on frequencies of SI-MUIEs: SI-MUIE which are evaluated in detail, and SI-MUIEs which are evaluated in a simplified manner in Task(f).

The frequencies of SI-MUIEs vary with seismic intensities, so the importance of SI-MUIEs varies with seismic intensities. If the classification is performed for each seismic intensity, risk significances of SI-MUIE are swapped depending on the seismic intensities, and the size of PRA model construction is not practically reducible. Also, when the results are viewed across intensities, they may not maintain consistency. Therefore, it is necessary to limit the seismic acceleration range to focus on. In this paper, we propose to focus on the medium acceleration range where CCDPs are rapidly rising. The reasons are as follows.

- In the low-acceleration range, random failures are dominant as a cause of mitigation system failures. That is, component failures due to seismic events are not significant in terms of CDF. Therefore, the importance of a detailed evaluation of that range is relatively low.
- In the high-acceleration range, some component failure probabilities and CCDPs due to seismic events are almost one. The risk insights obtained in this range, which can be used to improve safety, etc., are limited, and the importance of detailed evaluation is relatively low.

Task (f): Brief CDF assessment

The risks from SI-MUIEs subject to simplified evaluation are summed up when estimating risk metrics. In brief CDF assessment, conservative CCDPs are set in view of the purpose of the assessment, and a CDF for each SI-MUIE is obtained by the product of SI-MUIE frequencies and those conservative $CCDP_{mu}$.

The $CCDP_{mu}$ is obtained by taking the product of the conservative CCDPs from seismic SUPRAs. The conservative CCDPs are estimated by using a result assuming that all possible inter-unit interactions in seismic SUPRA occurred (e.g., all shared equipment is not available, no other unit support is expected, and a high-stress condition is assumed for all HFEs).

Task (g): Construction of seismic MUPRA model

This task conducts the element evaluation specific to seismic MUPRA, such as multi-unit human reliability assessment (MU-HRA), common-cause failure (CCF) assessment of SSCs in different units, and joint failure probability estimation considering response/capacity correlations subject to SI-MUIE selected in Task (e), and constructs MU-AS models. Details of these evaluation methods and examples are given in [6].

Multi-unit human reliability analysis

In an MU accident, the factors of human behaviour, such as the impact of stress, may differ for accident. In addition, some actions have similarities or dependencies among actions for each unit, even if they are done in each unit. Therefore, this task evaluates impacts on HEPs under MU accident conditions and also evaluates the dependency of human failure event (HFE) across units.

First, this task estimates a screening HEP based on HEPs of seismic SUPRAs, conducts a brief dependency assessment, and identifies MU risk significant HFEs through conducting temporarily MUPRA. Then, detailed HRA is performed on them, and an MUPRA model including HEPs and dependencies is updated.

Inter-unit common-cause failure evaluation

This task identifies common-cause component groups (CCCGs) in SSCs among units and estimates inter-unit CCF probabilities. It is assumed that commonalities of SSCs among units are smaller than those between redundant SSCs within a unit because there are some differences in operation durations and situations regardless of the same type of plant. Therefore, in the evaluation of inter-unit CCF probabilities, the following items are incorporated into the conventional CCF models:

- Impact of surveillance testing
- Impact of the degree of commonality of the Common Cause Coupling Factor (CCCF)

Joint failure probability evaluation

Seismic failures of SSCs do not necessarily occur independently; if there are correlations of responses and/or capacities among SSCs, joint failure probabilities of SSCs with correlations are higher than those without correlations. Therefore, joint failure probability estimations are performed with consideration of the correlation of response and/or capacities.

There have been some methods proposed; Representative methods include [13, 14, 15]. An appropriate method should be chosen considering ease of handling decision variables, computational complexity, and other factors.

Task (h): Quantification of MU-ASs

This task quantifies MU-ASs developed in "Task (g): Construction of seismic MUPRA Model." Inter-unit interactions can appear not only in MU-ASs that result in core damage in all units, but also in MU-ASs where some of the units successfully terminate. Therefore, all MU-ASs other than combinations of sequences which all units achieved successfully are subject to quantification.

First, an approximate estimation is performed for all MU-ASs. Based on the results, a detailed estimation is performed on the MU-ASs selected in Task (i). Both approximate and detailed estimations use the same logic model, and the differences of them are in truncation values and accuracy of quantification.

To obtain appropriate risk information, appropriate selecting of MU-AS quantification approach and success branch treatment is essential. An approach based on upper bound approximation and delete-term approximation is taken in the current seismic SUPRAs, but the approach overestimates when there are many basic events with a high probability and a large number of sequences. A more precise quantification approach is preferred which can appropriately account for success branches and can evaluate dependent events, especially in the case of detailed quantification.

Task(i): Screening of risk-significant MU-AS

As described in Task (g), the quantification of MU-ASs is performed in two steps in the proposed framework. This task selects risk-significant MU-ASs based on the results of the approximate estimation. The viewpoint of the screening is the same as the one in Task (e), that is, MU-ASs with a high frequency in the medium acceleration range and/or MU-ASs with a significant impact are selected. Then the MU-ASs are subject to detailed estimation.

Task (j): Organization and analysis of results, and Documentation

The results from Tasks (f) and (h) are compiled and the risk metrics are organized; since each MU-AS frequency is calculated separately, MU-AS frequencies are aggregated according to the definition of each risk metric. In addition, analysis of the quantification results and sensitivity analysis are conducted to validate the evaluation.

- Adequacy of assumptions that are not explicitly specified in the code of operation and set by analysts.
- Adequacy of screening criteria for SI-MUIE, HFE, and MU-AS subject to detailed evaluation
- Adequacy of truncation in MU-AS quantification
- Adequacy of engineering judgments

Finally, the purpose of the assessment, the scope of the assessment, the methods used, the assumptions used, the model, and the results of the assessment are documented. Documentation is to be in traceable detail.

4. CONCLUSION

This paper identified the requirements that seismic level 1 MUPRAs should have and MU events and inter-unit interactions that should be considered, and proposed a comprehensive framework for seismic level 1 MUPRAs. This framework was developed by extending that of internal event level 1 MUPRAs to seismic events. This framework was designed to balance the accuracy and implement cost by setting seismic SUPRA as the starting point of assessment and by clearly establishing the screening process. This framework enables a reasonable risk assessment for MU accidents due to seismic events.

References

[1] Vecchiarelli, J., Dinie K., and Luxat, J., DEVELOPMENT OF A WHOLE-SITE PSA METHODOLOGY, COG-13-9034-R0, CANDU Owners Group Inc., (2014).
[2] Zhou, T., Modarres, M., and Droguett, E. L., Multi-unit nuclear power plant probabilistic risk assessment: A comprehensive survey, Reliability Engineering and System Safety, Vol. 213 (2021), p. 107782.
[3] Hakata, T., Seismic PSA method for multiple nuclear power plants in a site, Reliability Engineering and System Safety Vol. 92, No. 7 (2007), pp. 883-894.
[4] International Atomic Energy Agency, Multi-unit Probabilistic Safety Assessment, Safety Report Series No. 110, IAEA, Vienna, (2023).

[5] Ebisawa, K. Teragaki, T., Nomura S., Abe H., Shigemori M., and Shimomoto M., Concept and methodology for evaluating core damage frequency considering failure correlation at multi units and sites and its application, Nuclear Engineering and Design, Vol. 288 (2015)

[6] Miura, H., Soga, S., Higo, E., and Kirimoto, Y., Development of Methods for Internal event level 1 Multi-unit PRA, CRIEPI report NR22003, (2023), https://criepi.denken.or.jp/hokokusho/pb/reportDlConf?reportNoUkCode=NR22003&tenpuTypeCode=40&seqNo=2.

[7] Miura H., Soga S., and Higo, E., An evaluation method for a seismic-induced multi-unit initiating event extending an initiating event classification tree for a nuclear power station, Mechanical Engineering Journal 11.2 (2024): 23-00415.

[8] Soga, S., Higo, E., and Miura, H., Theoretical comparison of models for a seismically induced joint failure probability, International conference on Probabilistic Safety Assessment and Management: PSAM 16 (2022).

[9] Muhlheim, M.D., Flanagan, G. F., and Poore III, W. P., Initiating Events for Multi-Reactor Plant Sites, ORNL/TM-2014/533, (2014).

[10] Kiper, K., and Maioli, A., A Framework for Addressing Site Integrated Risk, International Topical Meeting on Probabilistic Safety Assessment and Analysis: PSA 2015 (2015).

[11] Schroer S. and Modarres M., An event classification schema for evaluating site risk in a multi-unit nuclear power plant probabilistic risk assessment, Reliability Engineering and System Safety, Vol. 117 (2013), pp. 40-51.

[12] Soga, S., Higo, E., Miura, H., A systematic Approach to Estimate an Inter-unit Common-Cause Failure Probability, Reliability Engineering and Systemu Safety, 215(2021): 107802.

[13] J. W. Reed, M. W. McCann, J. Iihara, et al., Analytical techniques for performing probabilistic seismic risk assessment of nuclear power plants, International conference on structural safety and reliability; Kobe (Japan); 27-29 May 1985.

[14] P. D. Smith, R.G. Dong, D.L. Bernreuter, et al. NUREG/CR-2015: Seismic safety margins research program: Phase I: Final Report-Overview. Washington, DC; 1981.

[15] T. Uchiyama, T. Oikawa, M. Kondo, et al., User’s Manual of SECOM2: A Computer Code for Seismic System Reliability Analysis (in Japanese), JAERI-DATA/CODE--2002-011, 2002.