A Study of Multi-Unit Seismic Probabilistic Risk Assessment

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Abstract: The objective of this paper is to summarize a hybrid approach to external event probabilistic risk assessment for multi-unit sites considering multi-unit dependencies. It is addressed the issues existing in the current methods for seismic dependency modeling and seismic risk quantification. In this approach, the seismic-induced dependencies among the correlated structures, systems and components (SSCs) are properly considered at the group level using the simulation-based scheme that integrates the copula notion, importance sampling and parallel Monte Carlo simulation. Further, the discretization-based scheme in the proposed approach allows for the use of standard PRA software tools (i.e., SAPHIRE) to determine the site-level fragilities. In doing so, a balance between estimation accuracy and computational simplicity is achieved. A three-component example is presented to demonstrate the parametric estimation in the group level, and a case study is summarized to demonstrate the application to seismic site risk estimation. It is demonstrated that the effect of the seismic capacity of SSCs on site safety is more important in the midrange of PGAs, and the Total Site Core Damage Frequency (CDF) would be an appropriate multi-unit CDF metric for seismic risk.

Keywords: PRA, External Event, Seismic, Common Cause Failures, Multi-Unit Nuclear Power Plant.

1. INTRODUCTION

The 2011 Fukushima Daiichi accident [1] drew attention to the need for consideration of multi-unit events involved multiple reactor units co-located on a site. The risk significance of multi-unit events is further confirmed by the U.S. operational experience that over 9% of the total Licensee Event Reports (LERs) between 2000 and 2011 affected multiple reactor units on a site [2]. As such, the urgency has been highlighted to develop methodologies for multi-unit probabilistic risk assessment (MUPRA) to assess site risk profile considering the impacts of multi-unit events [3]. The interested readers can find a holistic review of state-of-the-art MUPRA [4], which summarizes the relevant activities to develop MUPRA methodologies and discusses the different facets of MUPRA research including multi-unit event, MUPRA modeling and site-based risk metric.

Recent research [5, 6] and operational experience [7, 8] have recognized external event as the most likely dominant multi-unit events. Among these, seismic events have received a lot of attention because of their likelihood to induce multi-unit dependencies with significant consequences [9, 10, 11]. The occurrence of an earthquake imposes strong spatial correlations on structures, systems and components (SSCs) either in the same or different reactor units. Identical or similar SSCs will behave in analogous ways [12], tending to fail together due to the dependencies that arise from the similarities in ground motion, seismic demand and seismic capacity, respectively. Therefore, the main challenge is to appropriately specify the degree of dependency and incorporate these dependent effects into the seismic MUPRA.

As the convention practice, one must either assume that the seismic failures are fully independent, or assume that such failures are completely dependent, both of which are inaccurate, with the truth lying somewhere in between. This is referred to as the partial dependent case. There are four approaches [11] in the present literature to account for such case of partial dependencies. However, there is no common agreement and the adequacy of the current methods for seismic dependency modeling in MUPRA was discussed in the authors' previous research [13]. In References 11 and 13, the interested readers can find more details on the existing issues with demonstrations in the current practice.

To address these issues, this paper summarizes an improved hybrid approach to assess site risk profile by characterizing seismic-induced dependencies. In this approach, the seismic-induced dependencies among the correlated SSCs can be properly considered at the group level using the simulation-based scheme that integrates the copula notion [14], importance sampling [15] and parallel Monte Carlo simulation [16]. Further, the discretization-based scheme in the proposed approach allows for the use of standard PRA software tools as a matter of practicality to determine the site-level fragilities and allows transfer of the results from level-1 PRA to level-2 PRA. In all, this approach achieves a balance between risk estimation accuracy and computational simplicity, and can also be extended to address other external events involved in the MUPRA.

This paper is organized as follows. Section 2 briefly summarizes the proposed approach to model the seismic-induced dependencies at the group level based on the copula notion and importance sampling, and to quantify the site-level fragility using standard PRA software tools such as SAPHIRE [17]. In Section 3, a three-component example is demonstrated for parametric estimation at the group level, and a case study is summarized for a seismic-induced scenario for a hypothetical two-unit site. Section 4 presents the conclusions. All the simulations are performed using the open-source language and computing environment R [18].

2. SUMMARY OF PROPOSED APPROACH

The proposed approach quantifies the site-level fragility by integrating the mean seismic hazard curve with the mean fragility curve [19]. This hybrid scheme is used to take advantage of the simulation-based scheme to account for the dependencies at the group level, and then the discretization-based scheme is used to quantify the seismic risk at the site level. It is assumed that the generic fragilities are used, and the correlation or dependent features would be provided by the seismic fragility analysts by separating the common sources of uncertainties among the interested SSCs [5].

For a correlated group, the impacts of seismic-induced dependencies can be characterized by the conventional parametric method for common cause failure (CCF) modeling, thereafter, a set of CCF parameters need to be estimated in terms of a specific ground motion interval by constructing a simulation-based scenario under the given failure criteria. First, an importance sampling method is used to tackle the ground motion intervals, which allows the propagation of uncertainty in the seismic hazard curve. Second, the copula notion is applied to construct the joint distribution of the ground acceleration capacity for the components with shared features. The constructed joint distribution is then used to randomly simulate correlated ground acceleration capacity. All the random sample sets are used to determine the parameter sets to characterize the effects of seismic-induced dependencies. Unlike the internal CCF modeling, the impacts of seismic-induced dependencies vary depending on the ground motion level and the capacities. Given the occurrence of an earthquake with certain ground motion level, a set of CCF parametric estimates would be determined to characterize the impact of seismic-induced dependencies. In this study, the β-factor model is adopted without loss of generality. As such, for each correlated group, one β-factor is derived to characterize the impact of seismic-induced dependencies at a specific ground motion interval.

To assess the multi-unit site risk, a discretization-based scheme is formulated considering the application of the standard PRA software tools like the SAPHIRE. Typically, the seismic hazard curve is discretized into several discrete intervals. To perform the parametric estimation of all correlated groups, one full Monte Carlo simulation is carried out for each correlated group regarding all discretized ground motion intervals. The parametric estimation process is parallelized so as to allow parallel computing to decrease the computational burden. A separate computational tool is developed using the R routing code to combine the simulation-based scheme with parallel Monte Carlo simulation. Specifically, the β-factor is then derived based on the results of the parallel Monte Carlo simulation and these parametric estimations are then input to the PRA model coded in SAPHIRE.

This hybrid approach achieves a balance between risk estimation accuracy and computational simplicity. First, the estimation accuracy is assured based on the improved characterization of seismic-induced dependencies when compared to the Reed-McCann method, and based on a justified selection of the reference ground motion level in the discretization-based scheme. Second, the computational simplicity is accomplished by the hybrid scheme, where any changes made in the MUPRA model, only the affected correlated groups or individual SSCs need to be modified to reflect the resulting changes in the risk estimates. This is more practical and efficient when compared with the conventional simulation-based scheme in which the whole system must be reconfigured in accordance with the required changes. This approach also ensures scalability of the MUPRA model, especially when dealing with complex seismic MUPRA models.

3. DEMONSTRATION AND RESULTS

3.1. Example Application to a Three-Component Group

Consider a common cause component group composed of three nominally identical components. The fragility of the component is described by the triplet vector [$A_m = 0.80, \beta_R = 0.25, \beta_U = 0.35$], where A_m is the median ground acceleration capacity, β_R and β_U are the logarithmic standard deviations [20]. It is assumed that the correlation coefficient between each component is 0.8. As displayed in Table 1, the seismic hazard curve is first discretized into twelve PGA intervals. Given each specific PGA interval, one β-factor is then derived to characterize the impact of seismic-induced dependencies.

Table 1: PGA Intervals and Frequency

Index	PGA Interval (g)	Reference PGA (g)	Frequency
1	0.05-0.25	0.25	1.80E-03
2	0.25-0.40	0.40	5.11E-05
3	0.40-0.50	0.50	1.21E-05
4	0.50-0.60	0.60	6.71E-06
5	0.60-0.70	0.70	4.10E-06
6	0.70-0.80	0.80	2.69E-06
7	0.80-0.90	0.90	1.86E-06
8	0.90-1.00	1.00	1.35E-06
9	1.00-1.05	1.05	5.37E-07
10	1.05-1.10	1.10	4.67E-07
11	1.10-1.15	1.15	4.09E-07
12	1.15-1.20	1.20	3.60E-07

The β-factor for this group is summarized in Figure 1 for all the twelve PGA intervals. In general, the β-factor is strongly dependent on the acceleration. In the low acceleration range, the β-factor is quite small and the SSCs in the system might be treated as independent. With increasing acceleration, the likelihood of concurrent failures increases rapidly. If compare to the conventional assumption of perfect dependency (i.e., setting β-factor to unity), it would be a highly conservative approach.

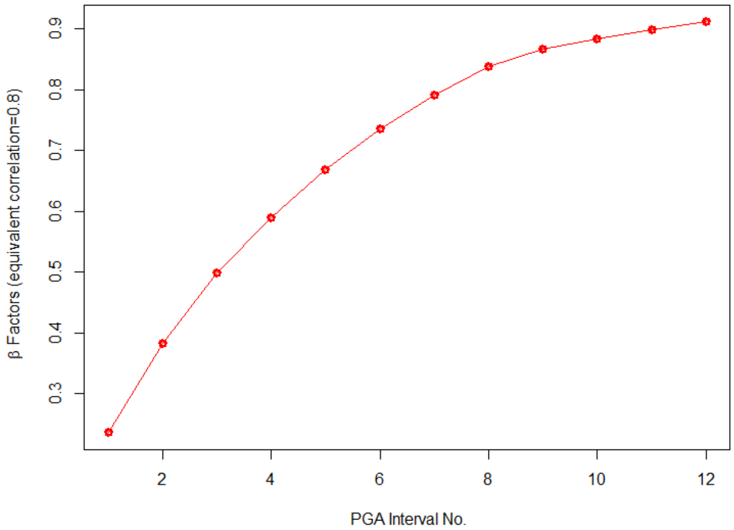

Figure 1: β-Factor for the Three-Component Group with Equivalent Correlation of 0.8

3.2. Example Application to a Two-Unit Site

To demonstrate the application to a multi-unit nuclear power site, a case study is developed that a seismic-induced accident scenario at a generic site consisting of two advanced reactor units at power. This involves three important elements as summarized below:

- *Multi-unit Accident Scenario*: the two reactor units are assumed to be identical and symmetrically constructed, and the Small Loss of Coolant Accident (SLOCA) is assumed to be caused by a seismic-induced break outside of the containment [21]. When considering the frequency of seismic-induced SLOCA, it is assumed that the seismic-induced SLOCA are fully correlated and the SLOCA initiating event frequency is estimated based on the generic conditional probability of occurrence of SLOCA developed from the piping calculations in the SSMRP [22].
- *MUPRA Model*: the seismic MUPRA model is established from the existing single-unit seismic PRA [21] by superimposing the seismic-induced multi-unit CCF between the identical SSCs across reactor units through the Level 1 fault trees according to the MUPRA methodology proposed by Modarres et al. [6].
- *Site-Based Risk Metric*: the multi-unit risk is characterized by the Total Site CDF, which is defined as the frequency of one or more core damage events; for instance, this definition corresponds to the union of the core damage events of Units 1 and Unit 2.

In this example, the seismic hazard data [23, 24] developed for the eastern United States were used and divided into ten PGA intervals as shown in Table 2. The reference PGA is selected as the upper limit of each discrete interval, and the frequency is calculated as the difference between the frequencies at the range limits of each interval. The SSCs' fragility data are employed from the generic fragility database available from published articles and reports [25, 26, 27].

Table 2: PGA Intervals and Frequency

Index	PGA Interval (g)	Reference PGA (g)	Exceedance Frequency (1/yr.)	Initiating Event SLOCA Frequency (1/yr.)
1	0.05-0.25	0.25	1.15E-03	5.75E-05
2	0.25-0.45	0.45	5.70E-05	3.42E-06
3	0.45-0.65	0.65	1.62E-05	3.23E-06
4	0.65-0.85	0.85	7.02E-06	2.81E-06
5	0.85-1.00	1.00	2.99E-06	1.91E-06
6	1.00-1.10	1.10	1.42E-06	1.08E-06
7	1.10-1.20	1.20	1.12E-06	9.87E-07
8	1.20-1.30	1.30	9.02E-07	8.20E-07
9	1.30-1.40	1.40	7.37E-07	7.37E-07
10	1.40-1.50	1.50	6.12E-07	6.12E-07

To investigate the influence of seismic-induced multi-unit CCFs between the SSCs across reactor units on the site risk, a sensitivity study was conducted to examine sensitivities to the assumptions regarding correlations of SSCs across reactor units. In the absence of information to support the correlation specifications, the equi-correlated model [28] is selected as a reasonable characterization model, which means that only one correlation coefficient needs to be specified between the similar or identical SSCs. Specifically, five correlation strengths cases are constructed across the reactor units: independent (i.e., 0), partial (i.e., 0.3, 0.5 and 0.8) and full dependency (i.e., 1.0), respectively.

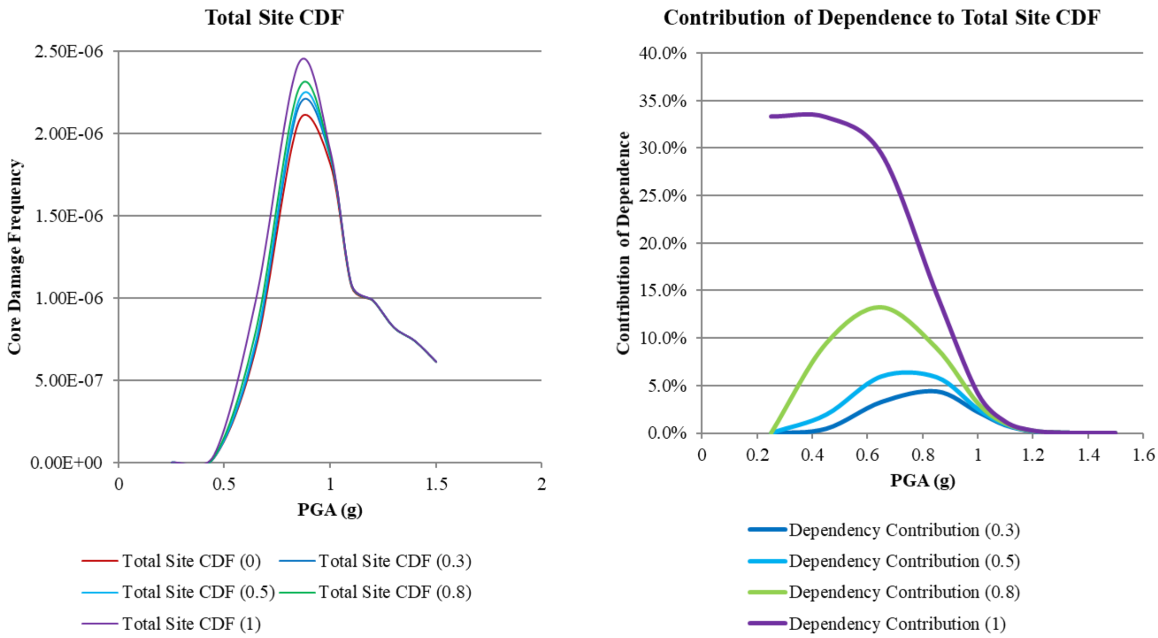

Figure 2: Results for the Total Site CDF VS. PGA

The software SAPHIRE is used to calculate the conditional core damage probability (CCDP) in each PGA interval, and the corresponding CDF is calculated by multiplying CCDP with the initiating event frequency of that PGA interval. The results are summarized in Figure 2 that shows the mean CDF estimates in terms of the five correlation strengths and show the contribution of dependency in each PGA interval. Furthermore, the final multi-unit CDF is then derived by summing the CDFs of all the PGA intervals, the results of which are displayed in Table 3 for all the five correlation strengths.

Table 3: Multi-unit CDF Results

Correlation Coefficient	Total Site CDF
0	8.83E-06
0.30	9.00E-06
0.50	9.07E-06
0.80	9.22E-06
1.00	9.59E-06

The results are useful to examine the impact of the correlation assumptions on the multi-unit risk metric and to identify the important risk contributors in different PGA levels as the correlation conditions vary. The important insights are summarized as below:

- The most sensitive region is the middle region of the site fragility curve with respect to the potential correlation assumption. Specifically, the effect of the seismic capacity of the SSCs on site safety is remarkable in the middle PGA interval around 0.3g to 0.5g. Ruggedizing components in this interval would enhance the site safety.
- It is less sensitive to both the low-end and high-end of the site fragility curve. It is intuitive to understand that an extremely large ground motion would lead to core damage simultaneously (i.e., setting β-factor to unity). Given the very low ground motion, there is rare seismic impacts (i.e., setting β-factor to zero) and the independent failures are dominant.
- At the higher correlations, the main sensitive region would be shifted to the lower end of the site fragility curve. The most important risk contributors would become the SSCs with lower fragilities and potentially higher correlations. Hence, reducing the degree of correlation for the relatively weak critical SSCs would help enhance the site safety.
- As displayed in Table 3, the perfect independent assumption would lead to 7.93% underestimation for the Total Site CDF metric when compared to the full correlation assumption. It indicates that the total site CDF metric could be used as a relative multi-unit CDF metric when no correlation data is available.

4. CONCLUSION

This paper presented an improved hybrid approach to evaluate the seismic multi-unit risk considering multi-unit dependencies, based on a hybrid scheme that integrates the copula notion, importance sampling, parallel Monte Carlo simulation and use of the standard PRA model and software tools. As such, a balance between estimation accuracy and computational simplicity is achieved in the proposed approach. Example studies were presented to demonstrate the application of proposed approach to the ground level and site level. Simulation, as well as sensitivity analysis, was performed to set the basis for studies of the impacts of seismic-induced dependencies on multi-unit site risk. The effect of the seismic capacity of SSCs on site safety was demonstrated to be more important in the midrange of PGAs. The Total Site CDF would be recommended as an appropriate multi-unit CDF metric for seismic risk.

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