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PARTIAL CORRELATION AND DEPENDENCE BETWEEN SEISMIC FRAGILITIES OF MULTIPLE ADJACENT STRUCTURES WITH SIGNIFICANT SOIL-STRUCTURE-INTERACTION EFFECTS

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MOTIVATION

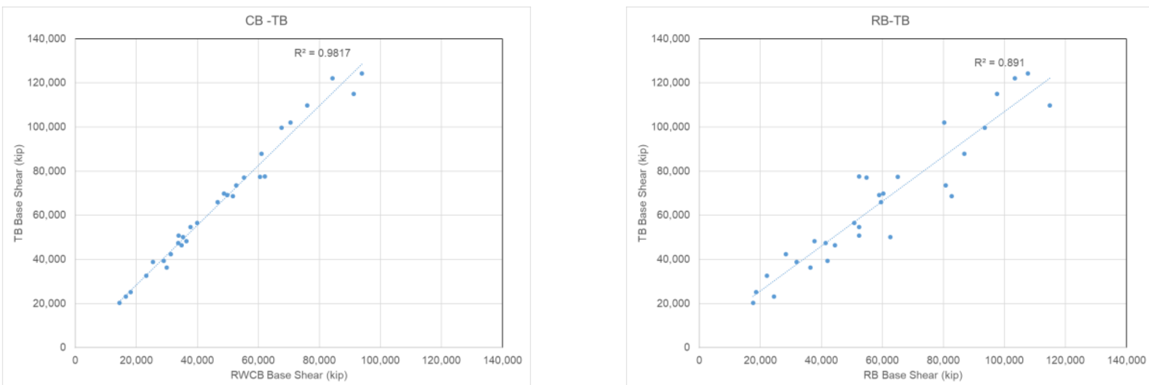
Seismic Probabilistic Risk Assessment (SPRA) of nuclear power plants (NPPs) is typically performed using three major analysis components: probabilistic seismic hazard, seismic fragility, and plant response. The fragility analysis develops conditional probabilities of failure for plant structures, systems, and components (SSCs) given ground motion intensity. Fragility combines the probability distributions of the strength of the SSC and the seismic demands given the ground motion intensity. The plant response analysis combines the seismic fragilities into a single plant-level fragility. In the plant logic model, the SSC failure events are typically modeled as either fully correlated or uncorrelated, but partial correlation is not explicitly modeled. Correlation is assigned based on judgment between components that experience similar seismic demands, e.g., co-located and oriented in the same direction, and have similar construction and anchorage (see Bohn and Lambright, 1990). Partial correlation between structure fragilities is often not considered, except maybe for co-located identical structures. This treatment is often conservatively biased, since modeling structure failures as independent typically increases seismic risk estimates. However, this conservative bias is often minor, since (1) partial correlation between structure fragilities is typically weak and (2) structure fragility contribution to NPP seismic risk is typically minor compared to other SSCs fragilities.

Recent SPRAs have shown an increasing contribution of structure fragilities to NPP risk, especially to that of large early release frequency (LERF). Modifications and upgrades to NPP equipment over time have made them more seismically robust while the buildings that house them did not change. For building structures founded on sites with significant-soil-structure interaction (SSI) effects, the SSI response is largely determined by the soil properties and the ground motions. Variability in these properties can have a significantly higher influence on the variability in seismic fragility than do structure properties and material strengths. Since the former factors are common to all the structures, their seismic fragilities can have strong partial correlation. Ignoring this correlation can result in overly conservative risk estimates.

PROBLEM DESCRIPTION

Preliminary risk insights in a recent SPRA project presented an exception to the convention reviewed above. The NPP LERF was dominated by structure failures of three adjacent buildings: the Reactor Building (RB), Control Building (CB) and Turbine Building (TB). Failure of the CB results in loss of command and control, which is required to recover from a serious accident sequence less robust than the CB failure. Collapse of the TB may result in severe damage and failure of the RB with a conditional probability of 0.20. The structure fragilities of all three structures were governed by inertia forces in the same ground motion direction. Variability in the structure base shear demands was dominated by the uncertainty in soil properties, which is common to all buildings. The latter two structures are founded at the same depth and have almost the same effective horizontal SSI frequencies, while the taller and heavier RB has an SSI frequency 33% lower. Preliminary sensitivity of the LERF estimate to modeling the structure fragilities as fully independent on the one hand and perfectly correlated on the other was on the order of a 50% difference. A realistic estimate of seismic risk required explicit modeling of dependence between these structure fragilities. This short paper presents a summary of this unconventional evaluation. The capacities and demands presented here are altered, while preserving the main parameters that influence partial correlation.

Figure 1 shows the correlation between seismic base shear demands of the CB-TB and the RB-TB pair from thirty probabilistic SSI response analyses with randomized properties and time histories. The CB-TB base shears are essentially perfectly correlated, while the other two pairs have strong correlation coefficients between 0.9 and 0.95, listed in Table 1 (the matrix is symmetric). The seismic fragility is modeled using a lognormal probability distribution, i.e., the natural logarithm of the ground motion capacity follows a normal distribution (EPRI, 2018). Table 2 shows the contributions of the variability in structure response, i.e., base shear, to the overall variability in the seismic fragility. The variability is characterised by logarithmic standard deviations, β_c (subscript c refers to the composite effect of multiple variables). The variability in structure response is clearly dominant compared to the other sources of variability.



(a) Control and Turbine Buildings (b) Reactor and Turbine Buildings

Figure 1. Correlation between Structure Seismic Base Shear Demands

Table 1: Random Variable Contributions to Structure Fragility Variabilities

Structure	Base Shear Demand			Ground Motion Capacity (All Fragility Variables)		
	RB	CB	TB	RB	CB	TB
Reactor Building	1	0.92	0.94	1	0.75	0.75
Control Building		1	0.99		1	0.95
Turbine Building			1			1

Table 2: Median Capacity and Random Variable Contributions to Structure Fragility

Seismic Fragility Parameter	Structure		
	RB	CB	TB
Median Ground Motion Capacity, A_m (g)	1.81	1.72	1.28
β_C from All Variables	0.52	0.81	0.58
β_C from SSI Response Variables	0.45	0.78	0.55
β_C from Strength Variables	0.20	0.21	0.12
β_C from Other Variables	0.17	0.06	0.14
β_C from Structure Response / Total β_C	**0.87**	**0.96**	**0.95**

SOLUTION STRATEGY

Rigorous evaluation of partial correlation coefficients for the entire random variable set is tedious and requires data that is often unavailable, as discussed in a recent state-of-the-art report on modelling of partial correlation in seismic fragilities (Budnitz et al., 2017). This paper presents two approaches that were used to develop a single composite fragility curve to represents the conditional probability of LERF due to seismic-induced failure in any of these three structures. This composite fragility curve was then used in the SPRA model as one fault tree node. The first approach was based on representing the partial correlations between the structure fragilities with logical dependence relationships between the failure probabilities instead of numerical-valued partial correlation coefficients between the ground motion capacity parameters. This practical alternative allowed the analytical development of a composite fragility curve in closed form. The second approach was to develop this composite fragility curve numerically using Monte Carlo Simulation (MCS) of partially correlated random variables, and was used to validate the analytical solution.

ANALYTICAL MODEL

The CB and TB fragilities are essentially perfectly correlated, but the variabilities in their seismic capacities are unequal. Accordingly, for ground motions less than 0.62g, the probability of CB failure is higher than that of TB collapse, and vice-versa (Figure 2a). Modelling them as perfectly correlated, at any ground motion the smaller of the two probabilities represents the probability that both fail, while the higher probability represents the probability that the more vulnerable of them fails. The ground motion space was thus subdivided into two zones, with the analytical solution developed separately for ground motions in each zone and then joined to form the composite fragility. The ground motion-specific logical dependence relationship between the CB failure and TB collapse events are shown using Venn diagrams in Figure 2b.

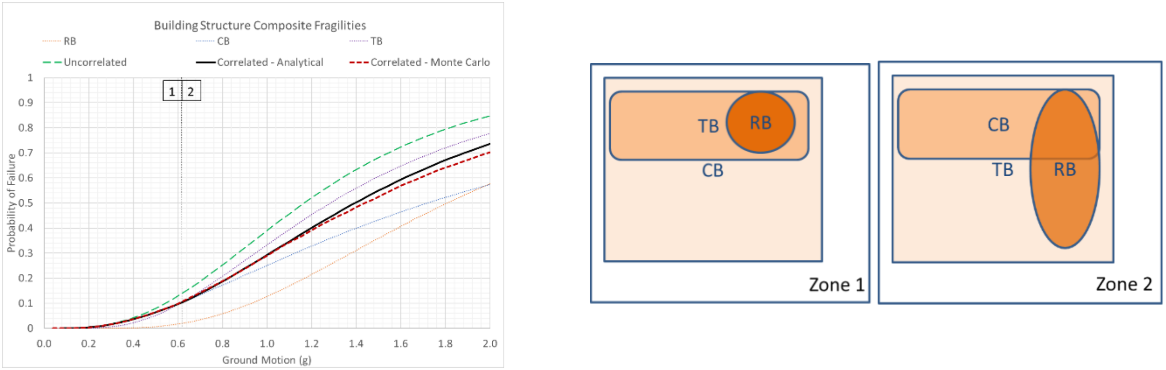
The RB and TB fragilities are strongly correlated. Their median seismic capacities are well-separated and the variabilities in these capacities are comparable (Table 2). Several independent simulations and sensitivity studies confirmed that, considering the partial correlation in the analysis data, the conditional probability of RB failure at any ground motion *given survival of the TB* is on the order of 0.001 or less, i.e., the RB almost certainly survives shaking if the TB does not collapse. If the TB collapses, the RB failure probability is the Boolean sum of the RB failure probability due to shaking and $D_{RB|TB}$ times the TB collapse probability, where $D_{RB|TB}$ = 0.20.

Characterizing the dependence between the RB and CB failures due to shaking is complex. There is not enough separation in the seismic capacities to allow making reliable statements similar to the other two structure pairs. This difficulty was overcome by recognizing that the RB failure event cannot occur independent of the TB collapse, which in turn has a well defined dependence relationship with the CB failure. In Zone 1 (Figure 2b), this dependence constrains the RB failure probability to being a subset of the CB failure probability, and it need not be quantified to develop the composite fragility. In Zone 2, a simplification was allowed where the RB and CB conditional failure probabilities given the TB collapse (Figure 2b) were treated as uncorrelated events. The accuracy of this simplification reduces when failure probabilities of the RB and CB increase at higher ground motions, which are nearly inconsequential to risk. While not explicitly input, this approach of decorrelating the *conditional* probabilities of RB and CB failure given TB collapse still enforces an implicit correlation on the RB and CB *marginal* (i.e., unconditional) fragilities. This constraint was found to correspond to a correlation coefficient of about 0.45, i.e., two-thirds of the estimated partial correlation coefficient in the seismic fragility (Table 1), which confirmed that this simplification was reasonable and slightly conservative. The composite fragility, i.e., mean conditional probability of failure, was then derived using the Law of Total Probability to be per Eq. 1 and quantified at discrete ground motions in a spreadsheet, where subscripts 1 and 2 refer to the logical dependence zones:

$$P(LERF|RB \cup CB \cup TB)_1 = P(CB)_1 \quad (1a)$$

$$P(LERF|RB \cup CB \cup TB)_2 = D_{RB|TB}P(TB)_2 + \left(1 - D_{RB|TB}\right)[P(RB)_2 + P(CB)_2 - P(RB)_2\,P(CB)_2/P(TB)_2] \quad (1b)$$

Figure 2a shows this composite fragility and compares it to the fragility computed considering that the three structure fragilities are independent per conventional practice, which is clearly conservative.



(a) Fragility Curves (b) Ground Motion-Specific Logical Dependence Models

Figure 2. Development of System-Level Composite Fragility for the Structure Failures

NUMERICAL MODEL

The MATLAB numerical simulation platform and statistical toolbox (MathWorks, 2017) was used to perform the MCS. The simulation used a sample size of 1 million randomly generated ground motion capacity vectors, $\{C_{RB}, C_{CB}, C_{TB}\}$. Each capacity vector was randomly generated from a joint normal distribution using the median seismic capacities (Table 2) in natural logarithm coordinates and logarithmic standard deviations, then transformed into linear space. Table 1 shows the correlation matrix used for the jointly simulated ground motion capacities. These values were estimated from the products of the base shear demand correlation coefficients and the percentages of SSI response analysis variabilities to the totals (Tables 1 and 2). This correlation matrix conservatively ignored potential partial correlations between other fragility variables, e.g., strength. Though there may be some positive correlation between these variables, its potential effect was found to be negligible. The more rigorous splitting of common and independent sources of variability discussed in Budnitz (2017) was not fully implemented since preliminary MCS trials to determine a stable sample size indicated low sensitivity to small differences in the correlation coefficient values. The role of the parameter $D_{RB|TB}$ was modelled by generating random indicator variables D_i equal to 0 or 1 from a Bernoulli distribution with a mean of 0.2. The conditional probability of failure on fractile composite fragility curves at discrete ground motions G_i was empirically estimated as the percentage of MCS simulations in which: $\{(C_{RB} \leq G_i)$ OR $(C_{CB} \leq G_i)$ OR $(C_{TB} \leq G_i$ AND $D_i = 1)\}$. Figure 2a compares the MCS-based mean composite fragility estimate to the analytical solution. The comparison shows an excellent match up to ground motions of about 1.1g. At higher ground motions, the analytical composite fragility is slightly more conservative. Ground motions higher than 1.1g had low contribution to LERF.

CONCLUSION

Ignoring partial correlation between structure fragilities introduces conservative bias in SPRA results. This bias may be significant at sites with significant SSI influence on response variability. This paper presented an analytical and a numerical approach to develop mean composite fragility whose results closely matched. The former is more practical and is valid if correlation can be represented using logical dependence models.

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