Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division VII

Probabilistic Modelling of Condensate Storage Tanks under Sequence of Main and Aftershocks Using Bayesian Network

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ABSTRACT

The risk of complex natural hazards such as a sequence of main and aftershocks needs to be evaluated accurately for essential structures supporting our societies. To quantify the risk by the sequential earthquakes, Mun and Song (2022) recently proposed a comprehensive probabilistic framework using Bayesian network (BN). This study applies the BN-based framework to condensate storage tanks (CSTs) in nuclear power plants. The development of the BN model is based on a procedure simulating the sequence of main and aftershocks and the evaluation of structural performances of the CST under ground motions. A simplified analytical model of liquid storage tanks is utilized for the dynamic analysis of the CST. By using the developed BN model, the seismic fragility of the system is evaluated for various scenarios of sequential earthquakes.

INTRODUCTION

In a sequence of earthquake events, the largest earthquake, termed mainshock, is followed by smaller earthquakes, termed aftershocks. Although the magnitudes of the aftershocks are generally smaller than those of their mainshock, the effects of the aftershocks on the total risk need to be quantified for essential infrastructures such as nuclear power plants (NPPs). Mun and Song (2022) recently proposed a new risk assessment framework based on Bayesian network (BN) for general systems under the sequence of main and aftershocks. In their work, important features of the sequence of main and aftershocks and structural performance are modelled in a BN model. Then, the relationships between the features are interpreted through the probabilistic inference capability of the BN model. Especially, seismic fragility, i.e., the conditional failure probability of a system given an intensity of ground motions, is evaluated for various earthquake scenarios of the sequential earthquakes.

This study applies the BN-based framework (Mun and Song 2022) to condensate storage tanks (CSTs), which are considered essential structures in NPPs (Choun et al. 2008). A CST structure located in the Ulchin NPP of South Korea is investigated as the case study system. To develop the BN model for the CST, dynamic responses of the CST are evaluated using a simplified analytical model of liquid storage tanks proposed in Malhotra et al. (2000). Then, the seismic fragility of the system is evaluated for various conditions under sequences of main and aftershocks through the probabilistic inference of the BN model. Specifically, the fragility is evaluated for the sequence of main and aftershocks as well as a single earthquake under the various mainshock scenarios. In addition, the failure probability of the system is evaluated for various cases of mainshock scenarios.

After brief introduction to the concept of BN methodology and the BN-based framework, this paper presents the development of the BN model for the CST including an introduction to the simplified analytical model developed for the dynamic analysis of the CST. Next, probabilistic inference using the BN model is presented to demonstrate the flexible evaluation of the system failure probabilities for various scenarios of the sequential earthquakes. Lastly, the paper is concluded with a summary and future research suggestions.

REVIEW: BN-BASED FRAMEWORK

Briefs on Bayesian Network

BN is a graphical model that is powerful in describing complex phenomena of real-world systems (Koller and Friedman 2009). In a BN model, random variables (RVs) and their dependency are visualized as nodes and directed arcs, respectively. Each RV is then modelled as the function of marginal probability or conditional probability given the variable it depends on. The joint probability of overall RVs is represented as the product of the probability functions.

For example, Figure 1 shows a BN model of three RVs $\{X_1, X_2, X_3\}$ for which the three probability functions $P(X_1)$, $P(X_2|X_1)$, and $P(X_3|X_1)$ need to be estimated. The joint probability of the RVs is represented as

$$P(X_1, X_2, X_3) = P(X_1)P(X_2|X_1)P(X_3|X_1) \quad (1)$$

where conditional independency, i.e., $P(X_3|X_1, X_2) = P(X_3|X_1)$ is assumed. This joint probability is used to evaluate the conditional probability of an RV given another RVs. This process is termed probabilistic inference in the BN methodology. The conditional independency assumption in BNs facilitates the modelling and inference of RVs, especially for large-scale BNs. Owing to these advantages, BNs are often utilized to deal with real-world engineering problems where multiple features are correlated with each other (Bayraktarli et al. 2005; Straub 2005).

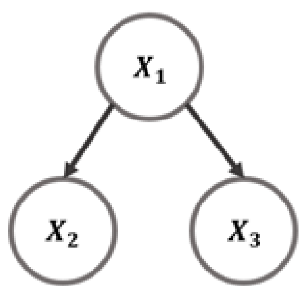

Figure 1. An example BN model

BN-based Framework for Structural Systems under a Sequence of Main and Aftershocks

Mun and Song (2022) recently proposed a BN-based framework for structural systems under a sequence of main and aftershocks. The BN model incorporates multiple features for the sequence of main and aftershocks and structural responses to earthquake ground motions. The basic element of the BN model consists of source and attenuation effects (EQ), general properties of ground motions ($\boldsymbol{\theta}$), and structural responses (EDP, Engineering Demand Parameter), which are modelled as a sequence of casual relationships such as $EQ \rightarrow \boldsymbol{\theta} \rightarrow EDP$. The model parameters of a stochastic ground motion model proposed in Rezaeian and Der Kiureghian (2010) are used to represent $\boldsymbol{\theta}$. The model parameters are matched with the six physical properties of ground motions, i.e., $\bar{I}_a$, D_{5-95}, t_{mid}, ω_{mid}, ω', and ζ_f. The first three features ($\bar{I}_a$, D_{5-95}, t_{mid}) and the others (ω_{mid}, ω', ζ_f) are related to the temporal and spectral properties of ground motions, respectively. More details on these model parameters can be found in Rezaeian and Der Kiureghian (2010).

The causal relationship of $EQ \rightarrow \boldsymbol{\theta}$ is represented for main and aftershocks using predictive models proposed in Rezaeian and Der Kiureghian (2010) and Hu et al. (2018), respectively. These models can predict the model parameters given a set of earthquake and site characteristics, i.e., fault type (F), moment magnitude (M), rupture distance (R_{Rup}), and shear-wave velocity (V_{s30}), which are used as EQ in the BN model. In other words, the predictive models are used to estimate conditional probability of $\boldsymbol{\theta}$ given EQ of main and aftershocks. Next, for the causal relationship of $\boldsymbol{\theta} \rightarrow EDP$, the conditional probability of EDP given $\boldsymbol{\theta}$ is estimated from dynamic analysis results for the ground motions generated within the domain of $\boldsymbol{\theta}$.

The sequence of causal relationships $EQ \rightarrow \boldsymbol{\theta} \rightarrow EDP$ are respectively modelled for main and aftershocks, and combined as a unified BN model as shown in Figure 2. The superscripts 1 and 2 in the figure indicate main and aftershock, respectively. The subscripts from 1 to n in EDP are introduced for complex systems for which multiple EDPs need to be investigated. In addition, an intensity measure (IM) of ground motions, e.g., peak ground acceleration (PGA), is incorporated as the child nodes of $\boldsymbol{\theta}$ for fragility analysis. To consider the correlation between the occurrence of main and aftershocks, EQ of the main and aftershocks are connected based on branching aftershock sequence (BASS) model (Turcotte et al. 2007). The BASS model can predict the occurrence of aftershocks given a mainshock scenario. Lastly, to consider the effects of structural damage from a mainshock on structural performances under aftershocks, damage state (DS) is incorporated into the BN model.

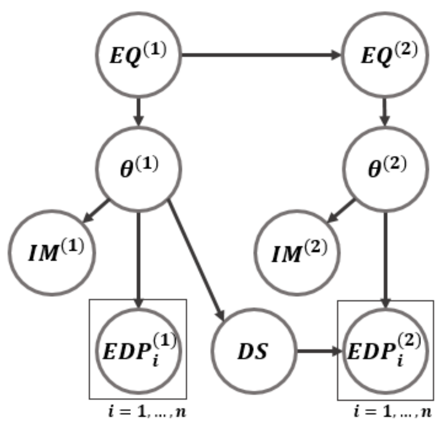

Figure 2. BN model of complex systems under the sequence of main and aftershocks

BN MODELLING FOR CONDENSATE STORAGE TANKS

Simplified Model of Condensate Storage Tanks

This study investigates CSTs that significantly contribute to system failure of NPPs under earthquake events (Choun et al. 2008). Given that high-fidelity finite element models demand excessive computational cost and the BN-based framework needs multiple dynamic analyses, a simplified analytical model is used to evaluate dynamic responses of the CSTs.

Dynamic behaviour of storage tanks filled with water is governed by water acting in two different parts. One of these is the convective part of water representing sloshing motion near the surface. The other is the impulsive part of water to move rigidly with the tank wall. In the simplified model proposed by Malhotra et al. (2000), the two parts of water are modelled as equivalent masses as shown in Figure 3. The amount of the equivalent masses and the dynamic properties of the masses are determined by the geometric properties of a target storage tank. The formulations to obtain the parameters in the simplified model are presented in Compagnoni and Curadelli (2018).

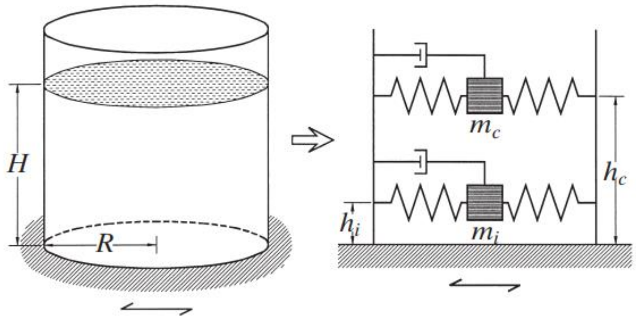

Figure 3. Simplified water-filled tank model by Malhotra et al. (2000)

In this study, a CST located in the Ulchin NPP of South Korea is investigated as a case study system. The CST is flat-bottom cylindrical tank partially filled with water as shown in Figure 4 (Nie et al. 2011; Fan et al. 2020). The geometric properties of the CST are listed in Table 1. The equivalent masses and other parameters of the target CST for the simplified analytical model are summarized in Table 2. The base shear and overturning moment of the CST to a seismic excitation are evaluated as the sum of forces induced by acceleration responses of convective and impulsive masses (Compagnoni and Curadelli 2018). This study uses the base shear and overturning moment as EDPs of the target CST in the development of the BN model.

Figure 4. The photo of the target CST adapted by Nie et al. (2011)

Table 1. The geometric properties of the target CST

Geometric properties	Values
Height of water	10.67m
Height of tank	11.43m
Inner radius of tank	7.62m
Thickness of tank wall	12.7mm
Density of water	1,000m^3

Table 2. The properties of the simplified CST model

Geometric properties	Convective component	Impulsive component
Equivalent mass	6.61×10^5kg	1.29×10^6kg
Natural frequency	8.88Hz	0.24Hz
Damping ratio	0.005	0.02
Height of the mass	7.16m	4.60m

Development of BN Model for Target CST

To develop the BN model in Figure 2 for the target CST, conditional probabilities of EDPs given $\boldsymbol{\theta}$ need to be quantified based on the dynamic analysis results. About 50,000 ground motions, generated for the various values of $\boldsymbol{\theta}$, are used to estimate the conditional probability of EDPs in the mainshock part. In general, the dynamic responses to aftershocks need to be evaluated considering structural damage from the preceding mainshock motion. However, in this study, given that the simplified analytical model is limited to represent the degraded behaviour of the CST, the two damage states, i.e., failure or no failure, are considered. If the system does not fail under a mainshock, the conditional probabilities of EDPs given $\boldsymbol{\theta}$ in aftershocks are the same as those of mainshock. However, when the system failed under mainshock, it is assumed that the system is still at a failed state without a retrofit strategy.

In this study, the conditional probability of each variable in the BN model is obtained so as to maximize the likelihood of data obtained from simulations, which are dealt with as discrete variables with prescribed intervals. Especially, modelling and inference of the BN model are performed using the matrix-based Bayesian network (Byun et al. 2019).

PROBABILISTIC INFERENCE USING THE DEVELOPED BN MODEL

Fragility Analysis for Mainshock

The BN model of the target CST can show various probabilistic inferences, especially for evaluating the seismic fragility of the CST. First, the fragility of the system for mainshock events is illustrated in this section, and then the system under the sequence of main and aftershocks will be investigated in the next section.

The BN model evaluates the fragility of the system by evaluating conditional probability of *EDP* given *IM*. Here, the effects of $\boldsymbol{\theta}$ and *EQ* on the relationship between *EDP* and *IM* are incorporated into the evaluation. This means that the fragility is evaluated for not only the given ground motions used for the development of the BN model but also other earthquake scenarios. For example, Figure 5 shows fragility outcomes of the CST for the failure events in terms of base shear and overturning moment where the limit states of the EDPs are assumed as 17,152kN and 208,87kN·m, respectively (Nie et al. 2010). In the figure, the red dotted lines for both of base shear and overturning moment represent the reference fragility outcomes from the raw data.

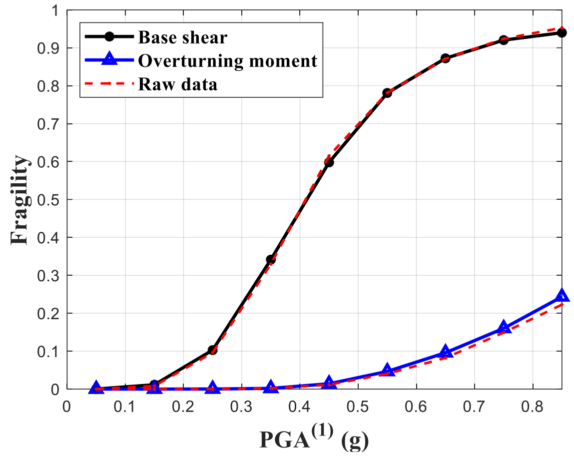

Figure 5. Fragility estimated by the developed BN model for the EDPs of base shear and overturning moment with raw data

Next, the fragility is evaluated for various earthquake scenarios by updating the conditional probability of $EDP^{(1)}$ given $IM^{(1)}$ for different values of $EQ^{(1)}$. For the purpose of illustration, we consider two mainshock scenarios that have different values of rupture distances and shear-wave velocities with the others held constant as follows:

$$\begin{aligned}&\text{Case 1: } F^{(1)} = \text{Strike-slip}, M^{(1)} = 7.0, R_{Rup}^{(1)} = 20\text{km}, V_{s30}^{(1)} = 360\text{m/s},\\&\text{Case 2: } F^{(1)} = \text{Strike-slip}, M^{(1)} = 7.0, R_{Rup}^{(1)} = 40\text{km}, V_{s30}^{(1)} = 760\text{m/s}.\end{aligned} \quad (2)$$

Figure 6 shows the fragility outcomes for the mainshock scenarios Case 1 (left) and Case 2 (right) in Eq. 2. The results show that the fragility outcomes in both of base shear and overturning moment become larger when the mainshock scenario is more severe. This means that the BN model can represent the causal relationships between the features in the BN model, and quantify the effects of the features on the seismic fragility.

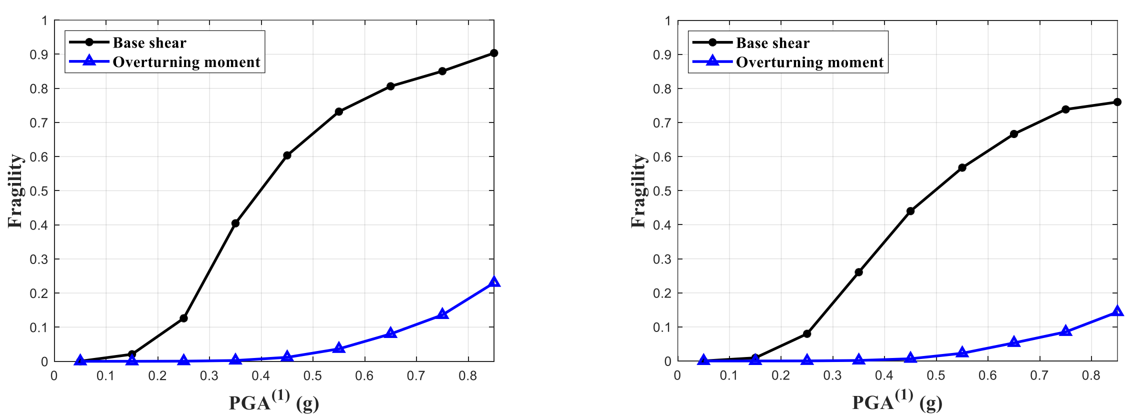

Figure 6. Fragility estimated for Case 1 (left) and Case 2 (right)

Fragility Analysis for Sequence of Main and Aftershocks

To consider the risk of aftershocks, the seismic fragility of the CST under the sequence of main and aftershocks is evaluated based on the PGA of the mainshock. This fragility is also compared with the outcome we obtain considering mainshock only. Figure 7 shows the fragility outcomes of the EDP of base shear (black fragility curves in Figure 6) for the sequence of main and aftershocks (MS-AS) and mainshock (MS) in the two mainshock scenarios.

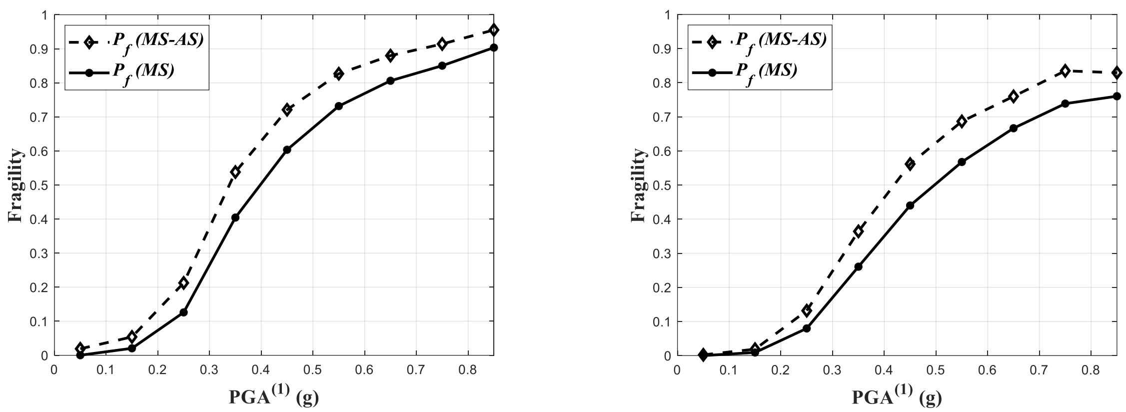

Figure 7. Fragility of the sequence of main and aftershocks (MS-AS) and mainshock (MS) for Case 1 (left) and Case 2 (right)

It is shown that the fragility outcomes increase when failure event under aftershocks is additionally considered. Here, the correlation between the aftershocks and the mainshock is considered in the BN model by updating probability of $EDP^{(2)}$ in the following sequence: $EQ^{(1)} \rightarrow EQ^{(2)} \rightarrow \boldsymbol{\theta}^{(2)} \rightarrow EDP^{(2)}$.

Lastly, the failure probability of the CST for the EDP of base shear is evaluated for the combinations of moment magnitudes 6, 7, and 8 and rupture distances 30km, 45km, and 60km of mainshock events while fault type (strike-slip) and shear-wave velocity (360m/s) are held constant. Figure 8 shows the failure probability outcomes.

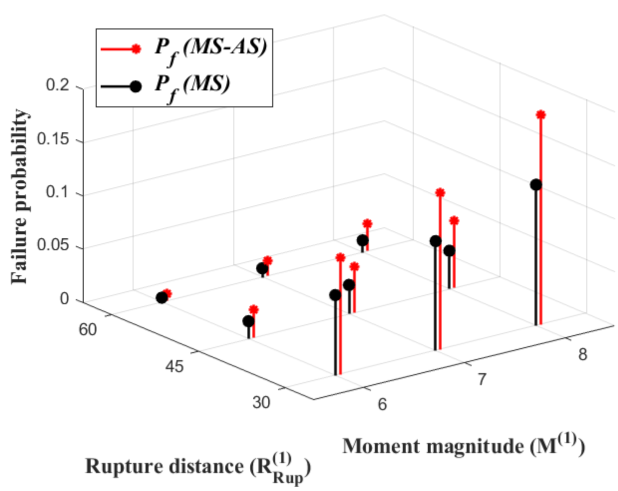

Figure 8. Failure probability of the CST for the combinations of moment magnitudes and rupture distances of mainshock event

CONCLUSIONS

In this study, the recently proposed BN-based framework was applied to a CST structure in a nuclear power plant. For the development of the BN model, a simplified analytical model of liquid storage tanks was utilized to analyze the dynamic responses of the CST to ground motions. Then, through the probabilistic inference capability of the BN model, the seismic fragility of the CST was evaluated for not only mainshock events but the sequence of main and aftershocks in various earthquake scenarios. Lastly, the failure probability of the system was evaluated for different moment magnitudes and rupture distances values. The proposed BN model is expected to enhance our ability to evaluate the risk of the sequential earthquakes and to make optimal risk-informed decisions. Future research topics include an extension of the BN model to other complex natural hazards, and the further development of the BN model for efficient and effective modelling of conditional probabilities given limited numbers of data set.

ACKNOWLEDGEMENT

This work is financially supported by Korea Ministry of Land, Infrastructure and Transport (MOLIT) as 「Innovative Talent Education Program for Smart City」 and the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by MOLIT (Grant 22RMPP-C163162-02).

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