

Bayesian Network-based Systematic Risk Evaluation for NPPs Subjected to Mainshock-Aftershock Sequences

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1. Introduction

Seismic risk for nuclear power plants (NPPs) is typically evaluated using seismic probabilistic safety assessment (SPSA), in which seismic hazard and system fragility are integrated to quantify risk. Conventional event tree (ET) and fault tree (FT) models provide an intuitive representation of system failure logic; however, they have limitations in representing dependencies and dynamically updating system states when additional information becomes available. These limitations are more significant when multiple or sequential hazards, such as mainshock-aftershock sequences, need to be considered.

Bayesian networks (BNs) are powerful for representing statistical dependencies among hazard and system variables and for updating their probabilities through inference [1,2]. In particular, a BN can explicitly connect earthquake characteristics to structural and system responses, which are generally treated separately in conventional SPSA.

This study develops an integrated BN framework for probabilistic modeling and inference of NPP systems subjected to mainshock-aftershock sequences. A BN describing the seismic sequence is first constructed using stochastic ground motion models. An NPP system model is then transformed into a BN and linked to the seismic hazard through component fragilities. The resulting integrated BN model enables scenario-specific evaluation of system failure probabilities considering both mainshock and aftershock effects.

2. Methods and Results

2.1 BN Model for Mainshock-Aftershock Sequences

The BN model for mainshock-aftershock sequences is constructed based on stochastic ground motion models for strong earthquakes and aftershocks [3-5]. The models generate ground motion time histories from earthquake source and site characteristics through intermediate ground motion parameters. These causal relationships are represented by directed links in the BN, ultimately providing peak ground acceleration (PGA) as the seismic intensity measure.

Separate causal paths are constructed for the mainshock and aftershock. Dependence between the two events is incorporated using the branching aftershock sequence (BASS) model [6], in which aftershock characteristics depend on the preceding mainshock characteristics. Consequently, the BN provides a probabilistic representation of PGA values for both events while preserving their physical and statistical dependence.

2.2 Integrated BN Model for NPP Systems

The Limerick Generating Station (LGS) system model [7] is considered as an example NPP system. Component failure probabilities are characterized by seismic fragility functions, and the original FT representation of the core melt (CM) event is converted into a BN by mapping OR and AND logic gates into corresponding conditional probability tables (CPTs) [2].

Because the seismic failure probability of each component depends on PGA, the basic-event nodes of the system BN are directly connected to the PGA nodes of the mainshock-aftershock sequence model. In addition, basic events under aftershocks are assumed to remain in a failed state if they have already failed during the mainshock. Two system responses, corresponding to CM caused by the mainshock and aftershock, are considered, and their union defines the overall CM event for the multi-hazard event.

The final BN model, as illustrated in Fig. 1, therefore represents the complete causal relationship from earthquake source and site characteristics to ground motion intensity, component failures, and the resulting system-level CM event. In addition, the BN inference capability allows the system risk to be updated for specified earthquake scenarios or observed information.

2.3 Scenario-Specific Risk Evaluation

The developed BN is used to evaluate the probability of CM for different mainshock scenarios as shown in Fig. 2. The fault type is assumed to be reverse for both the mainshock and aftershock, while the shear-wave velocity is considered within the range of 600-900 m/s. The CM probabilities are evaluated for different combinations of mainshock moment magnitude and rupture distance,

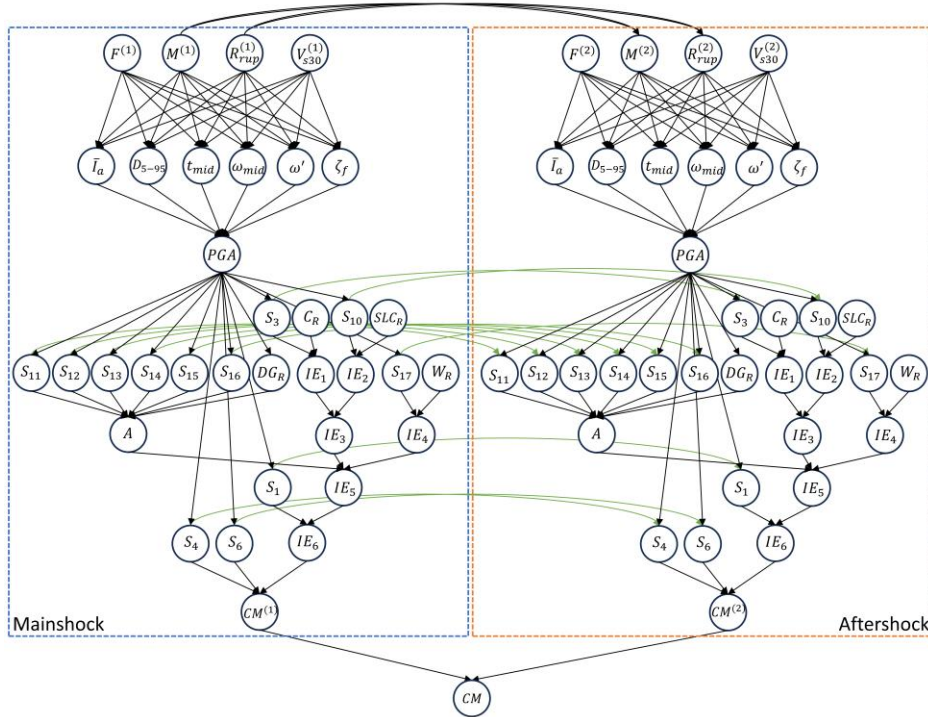


Fig. 1. Integrated BN model for the LGS NPP subjected to mainshock-aftershock sequences.

considering both the mainshock only (MS) and mainshock-aftershock sequence (MS-AS) failure cases.

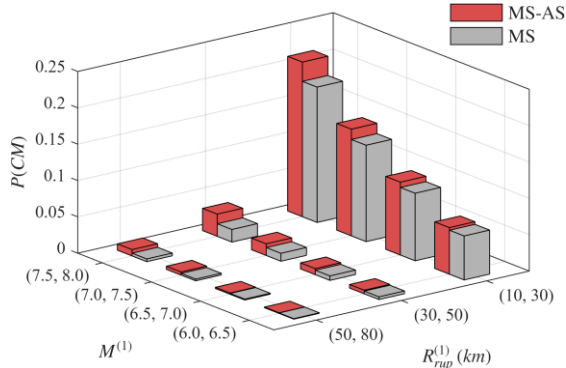


Fig. 2. Probability of CM for mainshock (MS) and mainshock-aftershock sequence (MS-AS) under different earthquake scenarios.

The results indicate that the contribution of aftershocks to the CM probability generally increases as the mainshock magnitude increases and the rupture distance decreases. This trend is attributed to the dependence between mainshock and aftershock characteristics represented by the BASS model, whereby stronger mainshocks tend to produce stronger subsequent aftershocks. The results demonstrate that the proposed BN framework can quantify the additional risk associated with aftershocks while explicitly accounting for earthquake scenario characteristics.

3. Conclusions

An integrated BN framework was developed for probabilistic modeling and risk assessment of NPP systems subjected to mainshock-aftershock sequences. The proposed framework combines sequential seismic hazards with an NPP system model within a BN model. This integration enables direct evaluation of system-level CM probabilities for specified earthquake scenarios and provides a flexible basis for probabilistic inference.

The application to the LGS system demonstrates that aftershocks can produce an appreciable increase in CM probability, particularly for larger mainshock magnitudes and shorter rupture distances. The proposed approach can be further extended to facilitate risk-informed decision-making following significant seismic events.

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