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Cross-entropy-based adaptive importance sampling for probabilistic seismic risk assessment of lifeline networks considering spatial correlation

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Abstract

There exist pressing research needs for developing sophisticated methodologies for probabilistic seismic risk assessment (PSRA) of complex lifeline networks, which are critical backbones of today's urban communities. In particular, ground-motion intensities at different locations of lifeline networks show significant variability and spatial-correlation, which should be properly considered in evaluating structural damage of lifeline networks and their corresponding network-level performance. In addition, the probabilities of the post-disaster states of the network often shows large variability, so simulation-based approaches may require a huge number of computational simulations if the set of the possible network states includes rare events. To improve the efficiency of simulation-based approach while maintaining its broad applicability, adaptive importance sampling methods have been recently introduced. In this study, a new PSRA approach is developed for lifeline networks by extending a cross-entropy-based adaptive importance sampling (CE-AIS) to estimate the probabilities of multiple possible states of the network utility concurrently. To test and demonstrate the proposed approach, a hypothetical traffic network under seismic hazard from surrounding active faults is investigated. The results of the numerical example show that the proposed approach, termed as CE-based concurrent AIS (CE-CAIS), identifies a near-optimal sampling density through only a few rounds of pre-sampling and drastically improves efficiency of simulation-based PSRA. It is also noted that CE-CAIS does not rely on a subjective intuition to select importance sampling density or require additional reliability analysis to identify important regions. The proposed method is expected to improve PSRA of lifeline networks in terms of efficiency and applicability, and provide new insights into the risk assessment and management of such urban infrastructures.

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Keywords: Lifeline network; Seismic risk; Cross-entropy-based adaptive importance sampling;

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1. Introduction

As observed in many earthquake disaster events, the post-disaster utility of a lifeline network is determined by the damage states of its structural components. To promote hazard-resilience of an urban community, the probabilistic assessment of the post-disaster loss in utility of social infrastructure is essential for the purpose of risk identification, resource preparation and recovery strategy at the community level. The network-level probabilistic seismic risk assessment (PSRA) often encounters technical challenges in identifying damaged structural components with their statistical dependence fully considered and integrating these into system-level analysis [1-6]. It is important to consider the statistical dependence between the failures of spatially distributed infrastructures in a regional PSRA because it is known that ignorance of these correlations tends to overestimate the risk of frequent events while underestimates that of rare ones. Therefore, the procedure of PSRA for lifeline network should include not only seismic fragilities of individual components, but also seismological properties at the sites and their spatially correlated aleatory uncertainties to capture the possible combinations of structural damages accurately.

Monte-Carlo Simulation (MCS) has been widely used for PSRA of lifeline network system, but this method may require a large number of simulations to obtain a reliable estimate for rare events. To overcome this issue, an importance sampling (IS) employing a data reduction technique was recently demonstrated [2] by shifting sampling densities and using *k*-means clustering for traffic flow analysis. Later, a map-selection technique was also proposed to reduce the number of simulations and computational cost by introducing a proxy measure capturing the features of damaged network [6]. As an alternative to the simulation-based approach, an analytical post-hazard analysis was performed for traffic flow capacity using the matrix based system reliability (MSR) method [3]. Some other examples of non-simulation-based approaches include the recursive decomposition algorithm to obtain narrow bounds on the probabilities of disconnection between source nodes and sink nodes [4], and multi-scale network clustering approach [5], developed to apply the approach in [4] to larger networks. Although these research efforts significantly improved the efficacy of PSRA of lifeline networks, simulation-based approaches have weakness in computational cost while applicability of analytical approaches is limited in terms of the complexity of the lifeline network topology, size and inherent uncertainties.

This paper provides an overview of an alternative simulation method the authors developed for PSRA of lifeline network, especially regarding traffic flow capacity under seismic hazard. In particular, the cross-entropy-based adaptive IS (CE-AIS) is extended to facilitate PSRA of lifeline networks. The proposed method does not require any heuristic judgement to perform IS while drastically reducing the number of samples to obtain converged estimates of probabilities. In addition, the proposed method aim to make the probabilities of multiple network utility states converge concurrently, and therefore is termed as CE-based “concurrent” AIS (CE-CAIS). A numerical example is provided to show the robustness and applicability of the proposed approach.

2. Modeling seismic hazard in uncorrelated standard normal space

For an accurate PSRA, the uncertainties in the followings need to be modeled properly:

- Magnitude of earthquake
- Location of rupture
- Intra-event residuals in ground-motion prediction equation (GMPE)
- Inter-event residuals in GMPE

PSRA incorporate these aleatory uncertainties into so-called ground-motion prediction equations (GMPE). A general form of GMPE is expressed as

$$\ln Y_{ij} = f(M_j, R_{ij}, \boldsymbol{\lambda}_i) + \sigma_{ij}\varepsilon_{ij} + \tau_j \eta_j \quad (1)$$

where Y_{ij} is the selected ground-motion intensity measure at site *i* for the earthquake event *j*, $f(M_j, R_{ij}, \boldsymbol{\lambda}_i)$ is the predicted mean value of Y_{ij} given as a function of M_j (magnitude of event *j*), R_{ij} (seismological distance to site *i* in