Multivariate Seismic Fragility Analysis of Curved Rocking Bridges using Active Learning-Enhanced Surrogate Modeling

Xueqi Zhong [a], Jianzhong Li [b], Feiyu Liao [a], Chiyu Jiao [c], Xu Chen [b]

[a] *College of Transportation and Civil Engineering, Fujian Agriculture and Forestry University, Fuzhou 350002, China*

[b] *State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China*

[c] *Engineering Structure and New Materials Research Center of Beijing Higher Education Institutions, Beijing University of Civil Engineering and Architecture, China*

Extended Abstract

Unlike straight bridges, the horizontal curvature of curved bridges induces complex bending-torsion coupling effects under dynamic loads, which may lead to significant damage to fixed piers (i.e., with fixed connection or integral construction to girder). Curved bridges with rocking piers offer enhanced seismic resilience but introduce complex interactions among horizontal curvature, bidirectional ground motion, and nonlinear rocking mechanisms, making traditional univariate fragility models insufficient.

To address these challenges, the proposed method integrates active learning with Natural Gradient Boosting (AL-NGB) to construct data-efficient surrogate models for seismic demand estimation under high-dimensional uncertainty. Framework for bridge system fragility assessment integrating NGB and active learning is shown in Fig. 1. The earthquake incident angle is particularly considered and incorporated in the multivariate seismic fragility analysis procedure, since this parameter is demonstrated critical for curved bridges.

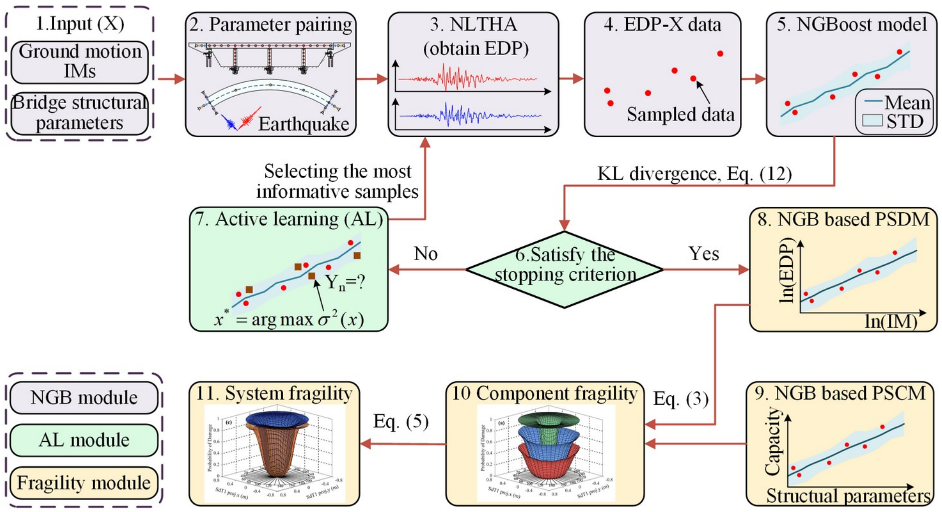

Fig. 1. Framework for bridge system fragility assessment integrating NGB and active learning

A comprehensive dataset comprising 2,000 curved rocking bridge models and scaled ground motions is developed to train and validate the surrogate framework. Feature selection via feature importance and correlation analysis identifies $S_{\text{d-T1}}$ and FI as dominant intensity measures. The proposed active learning scheme adaptively identifies and selects the most informative data points in successive iterations, guided by both predictive performance metrics and convergence criteria. With just 10% of the labeled data (150 out of 1,518 samples), the AL-NGB model achieves predictive accuracy comparable to the full-data NGB model.

The fragilities of the bearing, shear key, and abutment are strongly dependent on the incidence angle, while piers with circular cross-sections exhibit less sensitivity. Using only the horizontal components of ground motion along the bridge's principal axes may lead to an underestimation of component fragility. System-level seismic vulnerability of curved rocking bridges is strongly governed by critical components (e.g., shear keys) and is highly sensitive to the directionality of seismic excitation highlighting the need for direction-aware design. This study demonstrates the potential of combining active learning with probabilistic machine learning for data-efficient and high-fidelity seismic risk assessment of complex bridge systems.

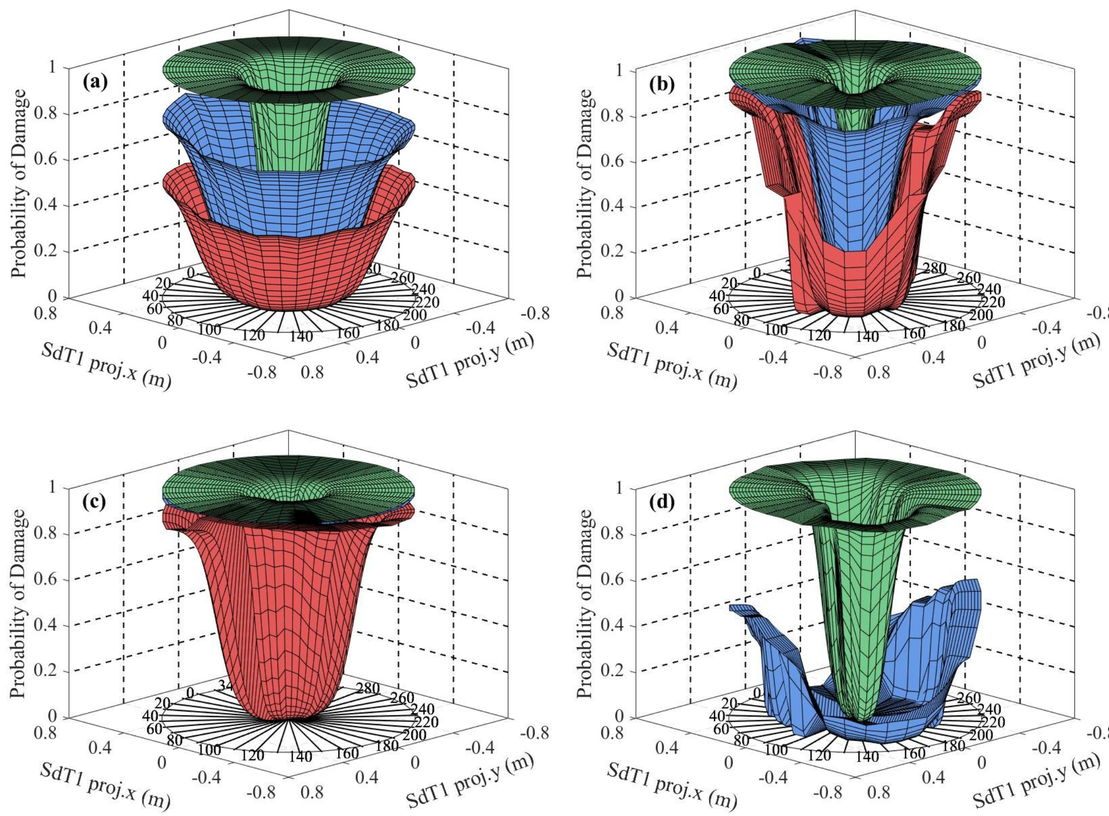

Fig. 2. Component fragility surfaces at different limit states for the: (a) pier, (b) bearing, (c) shear key, and (d) abutment (Green: LS1; blue: LS2; red: LS3; proj.: projection)

Keywords: *Curved rocking bridge; Seismic fragility analysis; Multivariate uncertainty; Machine learning; Active learning; Earthquake incidence angle*