SimCenter Community Roundtable
"Surrogate Modeling in Natural Hazards Engineering"

March 27, 2025

This SimCenter Community Roundtable meeting was organized by the **Working Group on Uncertainty Quantification (UQ) in Natural Hazards Engineering**. The meeting focused on the state of the art in surrogate modeling for natural hazards engineering to enable efficient, probabilistic assessment of risk in computationally intensive natural hazard simulations.

Surrogate models, also known as metamodels or emulators, have gained popularity for promoting computational efficiency across a wide range of applications for natural hazard risk assessment. They correspond to data-driven predictive models, and they are used to approximate the input/output relationship of a complex numerical model, based on an ensemble of simulations from that model representing the training data for the metamodel development. Depending on the setting, i.e. type of hazard and excitation/response characteristics, different types of metamodeling approaches can be deployed, ranging from deterministic surrogate models to stochastic emulation models, to series-to-series predictive models. This roundtable discussion provided a quick overview of the utility of metamodels in natural hazard risk assessment as well as of the key type of surrogate modeling techniques commonly encountered in natural hazards engineering. It showcased in more detail different surrogate modeling applications across different hazards and across different types of metamodeling approaches, combining a small number of invited presentations and an open dialog on this broader topic.

Host: Alexandros Taflanidis, University of Notre Dame

Presentations and Key Ideas

1. **"Overview of Surrogate Modeling for Natural Hazard Risk Assessment"**
   Presenter: Alexandros A. Taflanidis, University of Notre Dame.
   Prof. Taflanidis framed the discussion by highlighting the increasing use of high-fidelity numerical models in natural hazards analysis—and the challenges posed by their computational cost. Surrogate models offer a way to replace expensive simulations with fast approximations, provided they are carefully calibrated and validated. He cautioned against overreliance on black-box modeling, encouraging a deep understanding of input/output assumptions, variability, and model generalization. He also reviewed the fundamental surrogate model classes used in natural hazards engineering, from deterministic emulators to stochastic emulators, and from emulators for peak EDP predictions to emulators for time-series predictions.

2. **"Surrogate Modeling for Storm Surge Hazard Quantification"**
   Presenter: Norberto Nadal-Caraballo, U.S. Army Corps of Engineers.
   Dr. Nadal-Caraballo shared ongoing work in surrogate modeling of coastal storm surge using a physics-based modeling framework trained on storm suites. He described the use of parametric storm characteristics (e.g., landfall location, central pressure) to predict surge behavior across spatial and temporal domains. A dimensionality reduction technique (PCA) was used to project millions of spatial outputs into a latent space, enabling efficient Gaussian process emulation. Adaptive sampling and classifier integration improved performance. Results showed high accuracy in estimating coastal surge hazard compared to traditional high-fidelity modeling while requiring significantly fewer simulations.

3. **"Stochastic Emulation to Estimate Engineering Demand Parameters for Seismic Applications"**
   Presenter: Sang-ri Yi, University of California, Berkeley.
   Dr. Yi discussed stochastic emulation of engineering demand parameters (EDPs) in seismic applications for accurately capturing aleatoric uncertainty of the prediction (e.g., motion-to-motion variability). Gaussian Process (GP) model is extended to capture both epistemic and aleatory uncertainties without replicated simulations. Recently developed multi-output GP formulation was introduced to preserve correlations

between structural responses (e.g., drift and acceleration), improving risk estimation in systems sensitive to joint behavior. The surrogate model was validated in loss estimation problems and showed strong predictive performance even under constrained data availability.

4. **"Machine Learning Surrogates for Rapid Stochastic Trajectory Prediction in Nonlinear Structures Subject to Extreme Winds"**
   Presenter: Seymour M.J. Spence, University of Michigan.
   Dr. Spence presented a deep learning-based approach for rapidly predicting nonlinear structural responses under stochastic wind loading. By projecting both inputs (wind loads) and outputs (structural responses) into reduced-order latent spaces via proper orthogonal decomposition and wavelet transforms, the method trained LSTM neural networks to learn the mapping between reduced inputs and outputs. Applied to a 37-story high-rise building in NYC, the surrogate accurately reproduced time-history trajectories and peak responses across multiple degrees of freedom, even at fiber-section levels. The surrogate was shown to support probabilistic risk estimation under directional wind scenarios with excellent agreement to full simulations.

Discussion Highlights

- **Model validity:** Surrogates are not panaceas; they must be grounded in physics and domain knowledge to avoid extrapolation errors.
- **Scalability:** Limited simulation budgets make dimensionality reduction and active learning essential.
- **Multi-fidelity & hybrid models:** Combining high- and low-fidelity models offers promise in improving coverage while managing computational costs.
- **Uncertainty quantification:** Capturing both input variability and output correlation is critical for reliable risk assessment.
- **Emerging trends:** Participants expect increased use of physics-informed ML, adaptive surrogate training, and integrated modeling platforms within tools like SimCenter's WE-UQ and quoFEM.

More Information

Additional SimCenter Community Roundtable meetings can be found at https://simcenter.designsafe-ci.org/collaborate/scr/.

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