Causal Graph-based Joint Estimation of Ground Failure and Building Damage from Geospatial Prior Models and Satellite Imagery

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Rapid post-earthquake modeling and reconnaissance are important for response, recovery, and scientific endeavors by providing accurate and timely information concerning primary and secondary hazards and impacts, including faulting, landsliding, liquefaction, and building damage. Yet, despite extensive collections of existing geospatial datasets for prior events, data-driven empirical estimation methods suffer from low performance due to the complex and event-specific causal effects underlying the cascading processes of earthquake-triggered hazards and impacts. Physical models of the same suffer from the lack of spatially accurate physical model constraints, detailed exposure datasets, and model calibration. In contrast, satellite imagery-based impact assessments (e.g., NASA's Damage Proxy Maps, or DPMs), while spatially rich, lack the specificity as to what physical process caused from before-and-after imagery changes. We present the first rapid seismic multi-hazard and damage updating framework based on variational Bayesian causal inference and remotely sensed imagery. This framework enables accurate and high-resolution multi-hazard and damage estimates at a regional scale by jointly inferring primary and secondary hazards and resulting building damage and quantifying their causal dependencies from satellite images and prior models. Specifically, the underlying physical causal dependencies are modeled using a multi-layer causal Bayesian network. Furthermore, a stochastic variational inference algorithm is developed for simultaneously approximating posterior distributions of unobserved seismic hazards and impacts from the network. We evaluate our framework on multiple seismic events including the 2016 Central Italy, the 2018 Hokkaido, Japan, the 2019 Ridgecrest, and the 2020 Puerto Rico earthquakes to update model-based estimates of seismic landslide, liquefaction, and building damage using satellite image decorrelations. Our results are impressive, showing that our framework significantly improves the landslide prediction ability by up to 42% and our liquefaction prediction ability by up to 21%. It also reveals the event-specific causal dependencies among ground shaking, ground failures, building damage, and other environmental factors (herein treated as noise).

Key Words
DPMs, Graphical Model, Causal Discovery

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