Resilience of Coupled Urban Socio-Physical Systems to Disasters: A Data-Driven Modeling Approach

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Abstract

Cities face significant challenges in developing urban infrastructure systems in an inclusive, resilient, and sustainable manner, with rapid urbanization and increasing frequency of shocks (e.g., climate hazards, epidemics). The complex and dynamic interdependencies among urban social, technical, institutional, and natural components could cause disruptions to cascade across systems, and lead to heterogeneous recovery outcomes across communities and regions. Large scale data collected from mobile devices, including mobile phone GPS data, web search data, and social media data, allow us to observe urban dynamics before, during, and after disaster events in an unprecedented spatial-temporal granularity and scale. Despite these opportunities, we lack data-driven methods to understand the underlying mechanisms that govern the recovery and resilience of cities to shocks.

In this dissertation, I studied the recovery dynamics and resilience of urban systems to disasters using a large-scale human-centered data-driven modeling approach, with particular emphasis on the complex interdependencies among social, economic, and infrastructure systems. First, statistical analysis of large-scale human mobility data collected from over 1 million mobile phone devices in five major disaster events across the globe, revealed universal population recovery processes across regions and disasters, including disproportionate disaster effects based on income inequalities and urban-rural divide. Second, human mobility data are used to infer the recovery of various socio-economic systems after disasters. Using Bayesian causal inference models, regional and business sectoral inequalities in disaster recovery are quantified. Finally, the analysis on social, economic, and physical recovery were integrated into a dynamical model of coupled urban systems, which captures the bi-directional interdependencies among socio-economic and physical infrastructure systems during disaster recovery. Using the model and data collected from Puerto Rico during Hurricane Maria, a trade-off relationship in urban development is revealed, where developed cities with robust centralized infrastructure systems have higher recovery efficiency of critical services, however, have socio-economic networks with lower self-reliance during crises, which lead to loss of community resilience. Managing and balancing the socio-economic self-reliance alongside physical infrastructure robustness is key to resilience.

The proposed models and results presented in this dissertation lay the scientific foundations of urban complexity and resilience, encouraging us to move towards dynamical and complex systems modeling approaches, from conventional static index-based resilience metrics. Big data-driven, dynamical complex systems modeling approaches enable quantitative understanding of the underlying disaster recovery process (e.g., interdependencies, feedbacks, cascading effects) across a large spatial and temporal time scales, and is capable of informing urban development policies via cross-regional comparisons and counterfactual testing of recovery and urban resilience policies.