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PROGRESS AND CHALLENGES IN MODELING COMMUNITY RESILIENCE: AN UPDATE ON THE CENTER FOR RISK-BASED COMMUNITY RESILIENCE PLANNING

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The resilience of urban communities has garnered significant attention in industry, government, and academic research over the last decade. Recent events such as Hurricane Katrina in 2005, the 2011 Christchurch, New Zealand earthquake, the 2011 Great Tohoku, Japan earthquake and tsunami, Superstorm Sandy (2012), and other events worldwide have highlighted the need to better understand and model community resilience, including interdependencies among physical infrastructure components and systems that may exacerbate their lack of functionality following a damaging hazard event and delay community recovery and the dependence of supporting social and economic institutions on that physical infrastructure. In 2015, the National Institute of Standards and Technology (NIST) funded the multi-university five-year Center of Excellence for Risk-Based Community Resilience Planning (CoE), headquartered at Colorado State University. The Center's purpose is to develop the measurement science needed to understand what makes communities resilient and to develop a computational environment with fully integrated supporting databases that will enable resilience enhancement/planning and recovery strategies to be optimized. The approaches within the CoE couple engineering, sociology, and economics. This paper provides a brief overview of the CoE, including a summary of its accomplishments during its first three years and a discussion of several of the testbed communities that are being used to develop and test the measurement science underlying community resilience assessment.

Keywords: Community resilience, risk-informed decision, risk mitigation, community modeling

1 Introduction

The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado and involving a number of universities and nearly 90 investigators, was established as a Center of Excellence (CoE) by the National Institute of Standards and Technology (NIST) in 2015. The CoE's overarching goal is to establish the measurement science for identifying the factors that make a community resilient, to assess the likely impact of natural hazards on communities, and to develop risk-informed decision strategies that optimize both planning for and recovery from hazard events. To accomplish this goal, the CoE is engaged in three major research thrusts aimed at developing: (1) an Interconnected Networked Modeling Environment for Community Resilience (IN-CORE) to assess alternative community resilience strategies for improving community resilience; (2) standard data ontology, robust architecture, and management tools that support IN-CORE; and

(3) a comprehensive set of testbeds and hindcasts to validate the advanced modeling environment. This paper gives an overview of the CoE's research activities, including development of community resilience goals and metrics, modeling physical, social, and economic systems, and the effect of multiple hazards and cascading effects on systems performance and community resilience, including post-event recovery.

The CoE adopts the definition provided in U.S. Presidential Policy Directive 21 (PPD 21 available online at: https://www.dhs.gov/sites/default/files/publications/ISC-PPD-21-Implementation-White-Paper-2015-508.pdf) which defines resilience as *the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.*

The CoE is focused on natural hazards, including those less well defined for engineering analysis such as tornadoes, tsunamis, and wildland-urban interface (WUI) fires. To address the range of required topics, the research team includes university faculty, NIST researchers, research scientists, post-doctoral scholars, and graduate students. These topics include: (1) single, multiple, and cascading hazards modeled as scenarios at the community scale; (2) physical components and systems, including buildings, transportation networks, water and wastewater systems, energy networks, telecommunication networks, and their key geospatial and logical interdependencies; (3) aging and deterioration mechanisms; (4) economic modeling and cascading effects utilizing computable general equilibrium (CGE) models; (5) social systems and cascading effects including event impacts and recovery; (6) full model architecture validation using hindcasts; (7) optimization strategies for enhancing selection of community resilience alternatives; (8) an overarching resilience data management structure with a standardized data ontology and a community resilience glossary and taxonomy; (9) four exploratory testbeds ranging from a small Pacific Northwest town whose economy is tourist-driven to a large Metropolitan area of 1.4 million people; and (10) community resilience field studies to support the data and analysis architecture. In addition, an external assessment panel provides critical feedback bi-annually to the CoE leadership.

An overview is provided of progress in damage and community recovery modeling in the context of several testbeds that combine physics-based engineering models with post-event social and economic impacts. Recent work on IN-CORE development utilizing earthquake and tsunami models and on validation of the IN-CORE data architecture for the 2011 Joplin, Missouri, USA tornado is also presented.

2 Resilience Modeling Methods and Procedures Overview

Community resilience studies are, by their very nature, interdisciplinary and therefore can become quite complex to model accurately. Although each sector within the physical infrastructure can be modeled independently, their connectivity to other systems plays a key role in the recovery of a community. In order to model recovery, it is necessary to first model the existing condition of the physical, social, and economic systems in a community. From this baseline, a hazard scenario is applied for which damage and loss of functionality is predicted for the physical infrastructure networks including buildings, transportation, telecommunications, energy, and water/wastewater networks. These damage and functionality states then serve as initial conditions for recovery modeling. The physical infrastructure damages, in turn, are integrated into the CGE model so the temporal economic impacts can be measured. The social science effects related to population and employee dislocation, housing recovery, and business interruption, for example, can also be input to the CGE model to determine the impact on community recovery. The temporal resilience status of the community is indicated by community-level metrics identified by the CoE.

The IN-CORE computational environment is being developed as a research tool to allow resilience researchers to identify and understand the attributes that make communities resilient, identify recovery strategies that are effective across the physical-socio-economic domains, and study resilience science in general. IN-CORE can simulate the effect of various strategies for improving community resilience (e.g., reduced times to restore functionality). Optimal strategies can also be identified using a range of algorithms within IN-CORE for providing risk-informed decision support based on one or more hazard scenarios. The optimization methodology is not intended to endorse specific resilience improvement strategies, since these involve local socio-economic, political, and cultural factors and values that are difficult to model; rather, it is intended to provide a bounded number of choices that improve community resilience related to physical systems (e.g., transportation, water), socio-economics (e.g., housing, population, business), and the availability of services (e.g., healthcare). This process is being developed through application testbeds, each created for a different purpose, ranging from interdisciplinary analysis interfacing to recovery modeling and identification of key resilience metrics. The Interdependent Networked Community Resilience Modeling Environment (IN-CORE) will serve as a research tool for resilience researchers and eventually will provide a robust risk-informed platform for decision support. IN-CORE integrates a broad range of scientific, engineering, and observational data to produce a detailed assessment of the potential impact of hazards for risk mitigation, planning and recovery purposes. IN-CORE has the capability of computing resilience metrics to support decision-making at the user-desired community level. IN-CORE is an open source tool. The first version of IN-CORE is scheduled for full release in 2019 as a Java application with a plug-in based architecture that allows researchers to extend IN-CORE's capabilities through the addition of new science/features. These features can be connected with the existing 40+ analyses to produce new scientific results.

3 Community Resilience Testbeds and Hindcast within the Center of Excellence

The ***Centerville Virtual Community Testbed*** is an idealized community of 50,000 residents with an economy, infrastructure, and demographics intended to be representative of similarly sized communities. It provides a platform to demonstrate how individual infrastructure systems and their dependencies can be modeled, and how linkages between performance of buildings, transportation, energy, and water networks, and economic and social systems can be established for community resilience assessment purposes. An initial decision framework was developed for two simple problems involving pre-earthquake retrofit strategies in Centerville. The storyline for Centerville has been completed, and was published in a Special Issue in *Sustainable and Resilient Infrastructure* (Taylor & Francis, Vol. 1, Issue 3-4, December 2016). In addition, the Centerville testbed formed the basis for the development of a typical building portfolio consisting of 19 building archetypes, which is being used in other testbeds and hindcasts within the CoE. The Centerville testbed has been completed, and some research teams within the CoE are still utilizing it because of its simplicity.

The ***Seaside, Oregon Testbed*** considers a small coastal community with approximately 6,000 off-season residents and 10,000 buildings. It is being used as a test site to develop multi-hazard damage and loss assessments at a parcel scale for a range of earthquake and tsunami scenarios originating from the Cascadia Subduction Zone (CSZ). An independent probabilistic seismic hazard analyses (PSHA) and probabilistic tsunami hazard analyses (PTHA) were developed for Seaside. The team is using existing new ground fault motion equations (BC Hydro Model) for the earthquake scenarios that are used to initiate tsunami scenarios for a probabilistic seismic and tsunami hazard analysis (PSTHA). The electric power network modeling was improved following interviews with electrical engineers and the water and wastewater network was developed with the help of city engineers. A number of physics-based fragility curves for these networks were developed for tsunamis and for combined tsunami and earthquake hazards. The team is investigating the propagation of uncertainties for the PSTHA and a sensitivity analysis on the effect of model granularity (from tax lot level to census block level and beyond) for both hazards. Within the Seaside testbed, buildings and water network damage are being modeled interdependently with population dislocation to define (i) the population dislocation as a result of structural damage to buildings as well as building loss of functionality due to lack of water, and (ii) the temporal reduction in the water demand due to population dislocation. This testbed is also used to study the level of granularity needed in the modeling to capture spatial variability of the hazard impact and recovery while maintaining computational efficiency.

The ***Metropolitan Memphis Statistical Area Testbed***, which includes Shelby County, TN, is the first testbed involving a large, urban community. Memphis has about 700,000 residents; Shelby County has about 1 million; and the nine-county MMSA (Memphis Metropolitan Statistical Area), has about 1.4M. There are challenges in conducting functionality analyses (e.g., for water, power and traffic flow analyses) when small testbeds are used, such as those above, because the footprint of the water, power, and transportation networks are typically larger than the footprint of a small community. Thus, with a small community testbed, the functionality analyses for some infrastructure systems are difficult to conduct or assumptions are made about the "boundary conditions." The MMSA is addressing these challenges by considering a community with a larger footprint. The CGE model consists of eight distinct employment and residential areas that can accommodate natural hazards which have varying effects across the MMSA. The MMSA builds upon previous community resilience studies, branches out to the county and MMSA levels to examine the impact of support from adjacent communities on resilience, and examines the degree to which the modeling and analysis based on smaller testbeds can be scaled to an urban area. The MMSA testbed models the interfaces and information flow between physical, social and economic systems during the recovery process with an ultimate goal of informing the development of efficient decision support algorithms to support community resilience planning. Earthquake and flood hazards are being considered.

The ***Galveston, Texas Testbed*** integrates models ranging from hurricane hazard characterization and interdependent infrastructure modeling to social impact and population dislocation analysis. In particular, hazard modeling was performed for hurricane loads corresponding to storm surge and waves through two different approaches: (i) a scenario-basis that uses numerical simulations of complex hydrodynamic models and (ii) a probabilistic approach that utilizes surrogate modeling techniques. Additionally, a data-driven hurricane simulation scheme was developed based on an advanced wind model to simulate wind fields at the community scale. Data collection for building and infrastructure networks in Galveston were conducted. In particular, data for the residential building portfolio, and for water, telecommunication, electric power and transportation networks were acquired to support infrastructure modeling and damage assessment. This testbed is developing new fragility and restoration models (e.g. roadways, housing) to test network models that consider a range of interdependency types (e.g. functional, spatial). Post-event housing recovery modeling is being advanced using empirical findings from Hurricane Ike. The interdependencies affecting housing recovery, such as resource availability, social capacity, infrastructure system performance, and access, were identified from the data. Social vulnerability is being spatially analyzed through synthetic population approaches, to enhance modeling of social consequences based on recovery rates and resource availability.

Joplin, MO Hindcast: The objective of the Joplin Hindcast is to systematically validate the accuracy of IN-CORE modeling approaches of individual physical sectors, coupled sectors, social and economic sectors, and interactions for full events. On May 22, 2011, an EF-5 tornado (rated based on the Enhanced Fujita tornado intensity scale) cut more than a 10 km path of destruction through the city of Joplin, MO. With wind speeds of more than 360 km/h, the 1.2-km-wide tornado caused 161 fatalities, approximately 1,371 injuries and more than US $2.8 billion in losses, making it the deadliest and costliest single tornado in the U.S. since 1947. It should be noted that Doppler radar, and thus early warning for tornadoes, did not exist in 1947 as it did in 2011. A team from the CoE visited the City of Joplin and gathered a large amount of existing data from before and after the tornado to support hindcasting the event. The analyses use models that simulate tornado events based on historical data. The tornado models are applied to a series of analyses that are compared to data collected either immediately following the event or during Joplin's path to recovery. Analyses range from spatial building damage analysis which is compared to building inspection data following the event, to population dislocation based on wind speed using population data collected following a hurricane.

4 Future Plans

The CoE is at the beginning of Year 4 of a five-year program with a focus shift to risk-informed decision with the goal of identifying optimal pre- and post-event planning for Year 4 by summer 2018. An extensive number of conference papers and journal papers have resulted from the first three years of the CoE and a full list is available on the conference website at http://resilience.colostate.edu/publications_list.php.

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