MODELING COMMUNITY RESILIENCE: UPDATE ON THE CENTER FOR RISK-BASED COMMUNITY RESILIENCE PLANNING AND THE COMPUTATIONAL ENVIRONMENT IN-CORE

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Abstract

Community resilience is often defined as the ability of a community to prepare for, absorb, and recover rapidly from a hazard event. In 2015, the U.S. National Institute of Standards and Technology (NIST) funded the Center for Risk-Based Community Resilience Planning headquartered at Colorado State University, with the overarching objective of advancing measurement science related to community resilience through three objectives: (1) developing a computational environment that will allow researchers to identify attributes that resilient communities possess and make risk-informed decisions to enhance community resilience; (2) developing a standardized data ontology for managing diverse datasets and databases; and (3) conducting field studies and hindcasts to validate the computational environment. The Interconnected Networked Community Resilience Modeling Environment (IN-CORE), scheduled to be released at the end of 2019 as an open-source computational environment is the Center's main research product. IN-CORE utilizes the Jupyter Notebook where users can write Python scripts to call libraries, develop their own algorithms, and study community resilience. This paper introduces some of the special features of IN-CORE, highlights several testbeds related to earthquake and tsunami hazards that will serve as user examples in IN-CORE, reviews a joint Center-NIST longitudinal field study in progress, and outlines the development of a multidisciplinary glossary. The paper concludes with a summary of future tasks within the Center of Excellence and advancements in IN-CORE.

Keywords: community resilience; earthquake; tsunami; field studies; testbeds; IN-CORE; physical infrastructure; social institutions; economic modeling

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Overview of the NIST Center of Excellence: Scope and Purpose

Despite progress in science and technology aimed at improving the performance of the built environment during disasters, natural hazards in the United States are associated with significant losses and damage each year. To improve community resilience to natural hazards, each community or region needs a comprehensive resilience plan that specifies performance levels, land use planning practices, and timeframes for recovery of community functions while considering the diverse population characteristics and practices of any given place. Community resilience goals and policies should be based on the roles of its built environment and infrastructure in supporting desired social and economic functions that contribute to overall wellbeing and vitality within the community. However, science-based multidisciplinary modeling approaches, quantitative metrics, and data to support such metrics and models for evaluating community resilience are lacking.

The Community Resilience Group at the U.S. National Institute of Standards and Technology (NIST) is leading research to develop science-based tools to measure community resilience and support decision-making by communities and other stakeholders. The Group also is developing guidance to assist communities in formulating resilience plans as part of their long-range planning process and to identify options and assess alternative solutions based on standards, codes, and best practices.

In 2015, NIST funded the Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University and involving more than a dozen additional academic institutions across the nation, to collaborate with NIST on community resilience research. This is one of three NIST Centers of Excellence (CoE) and the only one funded to study community resilience. Key areas for technical advances include the following: (1) a modular, open-source computational environment (denoted as IN-CORE) that allows researchers to simulate impacts on and recovery of community functions, and to evaluate alternative solutions to support decision-making for a variety of hazard events; (2) data requirements for multi-disciplinary, temporal, geospatial analyses (from available databases and from field studies) and data management methods; and (3) protocols for field studies and qualitative and quantitative data collection methods and instruments for community-scale data.

This paper introduces IN-CORE, summarizes supporting testbeds related to earthquakes and tsunamis, highlights the integration of physical, social, and economic systems within a community as part of resilience measurement science, describes a longitudinal field study developed within the CoE in collaboration with NIST, and discusses next steps for the CoE research program.

The Interdependent Networked Community Resilience Modeling Environment (IN-CORE)

IN-CORE is a multidisciplinary computational environment with fully integrated supporting databases. IN-CORE will model the relevant factors that define community resilience through a set of core algorithms, and will allow users to develop their own algorithms, if necessary, in situations where local conditions warrant. This computational environment will support a comprehensive risk-informed decision framework for the optimal selection of strategies for enhancing community resilience. At the present time, it is being developed to be, first and foremost, a research tool to study community resilience

Building on previous research that focused primarily on the response of individual infrastructure components or systems to a single hazard, IN-CORE will consider multiple (inter)dependent physical systems, social, and economic systems subject to multiple hazards. IN-CORE is built on the recognition that the resilience of a community is dependent on these interconnected systems and, as such, provides a novel and holistic modeling environment and optimization approaches to better understand the levers that communities can use to improve their resilience.

IN-CORE consists of two major parts: 1) JupyterLab with a Python library (pyincore) and 2) web services. Users will be able to use the scientific models and web services in the JupyterLab environment. In addition, IN-CORE will allow advanced users to access the library and services via their local environments. IN-CORE will be released in 2019 as an open-source environment, where users will be able to integrate new algorithms and databases with the developed risk, loss, and recovery assessment capabilities.

IN-CORE Features. This section summarizes several significant features of IN-CORE; additional details can be found in Gardoni et al. (2018). ***Hazard Scenarios***: IN-CORE will allow the evaluation of different hazard scenarios, in which the spatial distribution of the hazard demands/intensity over a community is modeled. Both individual hazards as well as multiple hazards are considered, including: earthquakes, synoptic windstorms, tornadoes, hurricanes, wildfires, tsunamis, and floods. There will be two possible levels of modeling available, a Tier 1 and a Tier 2 model. The Tier 1 models will be based on standard hazard analysis formulations that run completely in IN-CORE using algorithms developed or implemented by the CoE. Tier 2 modeling will require running user-defined models outside of IN-CORE and then importing data into IN-CORE. ***Physical Infrastructure and Social and Economic Systems***: As noted previously, IN-CORE models physical infrastructure as well as social and economic systems. The physical infrastructure considered in this computation platform includes: buildings, transportation, water/wastewater, energy, and telecommunication systems. Fragility curves (for discrete elements) and repair rates (for line elements) are used to predict the physical damage, potential repair rates, and restoration times for a given hazard scenario, taking into account interdependencies in infrastructure performance. Models of social and economic systems currently focus on predicting population and employee dislocation, housing restoration and recovery, and business interruption and restoration. The models integrate information on the physical damage and reduction of functionality of the physical infrastructure with information on socio-demographic and socio-economic characteristics of the population. Spatial dynamic computable general equilibrium models are used to estimate the broad economic impacts of a hazard on a community. Examples of impacts considered include economic impacts, such as interruptions to production and job and wage losses, and their impacts on residents, including health, income and dislocation/migration. ***(Inter)dependencies and Damage Modeling***: IN-CORE will model the (inter)dependencies within and between physical infrastructure, and social and economic systems. The time evolution of the (inter)dependencies will also be modeled. For example, in terms of the physical infrastructure, the water-flow analysis, which defines the water available at each distribution node in the community, will include the dependency of the water system on the supporting energy system. This dependency plays a role in the definition of the initial damage scenario immediately following a hazard event and also shapes the recovery process. In addition, IN-CORE also models the time-varying (inter)dependencies between the physical infrastructure and social and economic systems. Finally, IN-CORE incorporates the effects of aging and deterioration in fragility and repair rates. Users will be able to provide site-specific input parameters that define the aging and deterioration mechanisms. ***Recovery Modeling, Performance Goals, and Resilience Metrics***: The recovery of communities has been modeled in IN-CORE. Further refinements to better understand recovery metrics includes incorporating additional interdependencies and validating models. These are currently underway. Community-level recovery will be quantified using resilience metrics defined by the CoE (or by other users of IN-CORE) to capture how well aspirational performance goals will be met. Table 1 gives a few examples of community performance goals and the associated resilience metrics.

Table 1. Examples of Community Performance Goals and Resilience Metrics

Community Performance Goals	*Resilience Metrics*
Population stability	Change in dislocation, jobs, and housing
Economic stability	Change in taxes and revenue (resources), and community budget (needs)
Social Services stability	Access to healthcare, education, retail, and banking
Physical Services stability	Functionality of buildings, transportation, water, wastewater, electric power, gas, and telecommunication
Governance stability	Access to police and fire protection; essential public governmental services

Decision and Optimization**:** Selected characteristics of the physical infrastructure and of the social and economic systems will be used as levers in optimization algorithms implemented in IN-CORE to optimize strategies for pre-hazard mitigation and post-hazard recovery. IN-CORE will ultimately be an analysis tool able to inform decision makers of the optimal use of resources to achieve desired performance goals.

IN-CORE Architecture. As indicated previously, IN-CORE is web-based and consists of two major parts: 1) JupyterLab with a Python library (pyincore) and 2) web services and modules. The JupyterLab with Python library (pyincore) provides modules to access the web services and modules for scientific algorithms/analyses, such as hazard scenarios, data, and fragilities. In the JupyterLab environment, users can create their own python script to combine and connect the scientific models and web services, or to add user-defined modules. The IN-CORE platform is implemented on cutting edge container technology such as Kubernates and Docker for elastic scalability and performance. In addition, IN-CORE allows advanced users to use the library and services on their local platform.

To support the development of fragility functions and general work flow in IN-CORE, and as an example of how IN-CORE can be used with existing open-source codes, a Python module for the OpenSees finite element software framework was developed. OpenSees is a general purpose finite element software framework originally created for simulating the response of structural systems to earthquake loading, but it has since grown to incorporate simulation models for other structural hazards such as fire and wave loading. CoE researchers abstracted the essential input and output functionality of OpenSees away from Tcl and created a general interpreter interface that accommodates Python as well as other scripting languages. The availability of a Python module allows IN-CORE users to simply import OpenSees and build models and perform analyses directly in their work flow, e.g., using Jupyter notebooks. Since IN-CORE provides a platform built on Python, scientific algorithms by CoE researchers and popular scientific Python libraries such as SciPy, NumPy, NetworkX, Pandas, GeoPandas, Pyomo, etc. can be used along with the OpenSees Python module.

Testbeds and Field Study

Testbeds can be virtual or real communities and are used to drive the thought process in developing modules and algorithms for IN-CORE. Field studies can be used to collect data for developing data-driven models or validating modules and algorithms. Each testbed serves a unique purpose within the CoE. The virtual community of Centerville was the first testbed within the CoE and launched the essential interdisciplinary collaboration between engineering and the social sciences within the CoE and allowed investigators to explore the sociology, urban planning, economics, and built environment dimensions of earthquake and tornado hazards. The Seaside Oregon testbed helped facilitate successive hazard modeling of earthquake followed by tsunami and the integration of physical infrastructure and social systems, and represents the smallest testbed by population. The Memphis Metropolitan Statistical Area is the largest of the testbeds and provides CoE researchers the ability to explore a complex urban area of more the 1M people, including investigations of scale and aggregation of physical and non-physical infrastructure. While other testbeds have been developed, the focus herein is on these three testbeds that represent those within the CoE associated with earthquake and/or tsunami. Readers are encouraged to explore the CoE webpages for information on the other testbeds and hindcasts at http://resilience.colostate.edu .

The Center's studies of the economic impact of natural hazards disasters on communities are based on highly spatialized Computable General Equilibrium (CGE) models that account for the unique spatial characteristics of a disaster within a community. The sources of data are the U.S. Census Bureau's Public Use Microdata Sample (PUMS), Quarterly Census of Employment and Wages (QCEW), County assessor's data, Comprehensive Annual Financial Records (CAFR), and the longitudinal employer-household dynamics dataset and the origin-destination employment statistics file (LODES). An open-source program has been developed by the economics team in collaboration with engineers and is being integrated into IN-CORE. The CGE model has been constructed to incorporate modeling results for the damage to buildings, electricity, water/wastewater, transportation and telecommunications so that the economic impact can be estimated for all these disruptions. Relevant extra-community level resources in the form of post-hazard event insurance and federal monies can be incorporated into the CGE model to assess potential recovery processes. In addition, methods are being developed that optimize mitigation policies based on community goals subject to financial and other constraints. Work is ongoing to refine metrics that provide community decision-makers information on four areas of community stability, namely population stability, economic stability, services stability, and physical infrastructure stability.

The CoE team has developed a number of models for capturing relevant social dimensions of community resilience. For example, important for engineering and social science modeling has been the development of approaches for generating stochastic household population data, along with important socio-demographic characteristics of households, at the housing unit level. These approaches for generating synthetic household population data at the housing unit level provide the possibility of modeling pre-event population data to engineering models of pre-event demand on community infrastructure systems such as water. These data are also being utilized in refined models of population dislocation and restoration that are informing post-impact infrastructure demand modeling from impact through restoration phases. Empirically-based statistical models of residential housing resilience capturing the consequences of loss/damage and other socio-economic factors for long-term housing economic recovery and restoration have been developed along with empirical models of business disruption and failure at the establishment level [Hamideh et al 2018]. In the future, the results of these newly developed models for population dislocation, housing recovery, and business failure and disruption will be implemented into the CGE model so that more accurate and nuanced estimates of the economic impacts of a natural disaster can be obtained.

The Centerville Virtual Community Testbed. The Centerville Virtual Community Testbed was initiated during the first year of the CoE research program to enable fundamental algorithms in IN-CORE to be initiated, developed in a preliminary form, and programmed and tested before the measurement methods, data ontology, and databases for modeling physical and social infrastructure systems and networks had fully matured. Centerville is a simple model community, intended to: (1) familiarize CoE researchers/developers with the scope of community resilience assessment in a context where solutions could be verified; (2) identify and test interfacing mechanisms between physical, social, and economic systems; (3) test simple hypotheses and the formulation of suitable response metrics related to social and economic stability; and (4) provide early information to IN-CORE programmers as to the likely forms of models and data to be supplied by different research tasks at later stages of CoE research.

Centerville is an archetype of a typical city of moderate size situated in a Midwestern State, with a population of approximately 50 000 and a median household income that is close to the national average of $52 000. The Centerville economy is diversified, and consists of a manufacturing sector, commercial/retail sectors, finance and professional services, health care, education, public services, and tourism. Centerville is susceptible to earthquake and tornado hazards. Engineers and social scientists associated with the CoE worked together to develop models for the building inventory, as well as for the potable water and electric power infrastructure, capturing their dependencies. The economic framework of Centerville was modeled using a computable general equilibrium (CGE) model. A decision framework was developed and tested successfully for two simple problems involving optimizing pre-earthquake retrofit strategies. The storyline for Centerville has been completed, and has been published in a Special Issue in *Sustainable and Resilient Infrastructure* [Vol. 1, Issue (3-4)]. The physical topology of

Centerville is available upon request with requesting instructions at: http://resilience.colostate.edu/data.shtml .

Seaside Oregon / Cascadia Subduction Zone Testbed. The Seaside Oregon Testbed can be used with IN-CORE for probabilistic seismic and tsunami damage analysis (PSTDA) due to both seismic motion (shaking) and tsunami inundation from tsunamigenic earthquake events at a coastal community. The Seaside Testbed considers tsunamigenic earthquake events originating from the Cascadia Subduction Zone (CSZ) and includes socio-economic data to illustrate the application of the framework. The PSTDA can be used for risk-informed decision making, including assessment of socio-economic loss to improve the resilience of communities from tsunamigenic earthquake disaster. In the case of tsunami induced damages, most of the highest damage probabilities are concentrated on the near coastline, and the level of damage weakens inland. The model can be used to evaluate the community risk to multi-hazards. The Seaside Testbed was used to develop models for the potable water infrastructure, the incorporation of detailed synthetic household characteristics that were derived from Census and other databases, and the integration of physical infrastructure and social systems in communities' reliability and resilience analysis within IN-CORE.

Memphis Metropolitan Statistical Area. The Memphis Metropolitan Statistical Area (MMSA) Testbed was developed to test the algorithms for community resilience assessment (developed earlier for relatively small testbeds) on a large urban area with a diverse economy and population. One objective of the MMSA Testbed was to advance the development of new algorithms. The populations of Memphis, Shelby County, and the MMSA are approximately, 0.7M, 1M and 1.4M, respectively. Considering a testbed with a larger footprint, as used here, permits more realistic functionality analyses.

A high-resolution topological model of Memphis, its physical and social infrastructure and the seismic hazards originating from the New Madrid Zone were developed in previous research [Elnashai et al, 2008]. The MMSA builds upon this previous work, extending the community model to the surrounding MMSA county levels, examining the impact on urban resilience of interconnected infrastructure systems and support from the surrounding communities, and illustrating the limitations in extending algorithms developed from smaller testbed scale to a real urban area.

One of the distinguishing features of IN-CORE, as mentioned earlier, is its ability to perform resilience analyses using models of differing levels of sophistication. Tier 1 and Tier 2 modules, as previously defined, are being investigated within MMSA, beginning with two alternative earthquake ground motion models. The first determines the ground motion intensity using a traditional approach, in which the (random) seismic intensity is determined as a function of moment magnitude and epicentral distance. The second utilizes high-resolution, 3-dimensional (3D), physics-based models for seismic wave propagation under realistic tectonic and geo-morphological conditions, suitable for the assessment of spatially distributed earthquake demands on distributed infrastructure.

Field Study to Validate Recovery Algorithms. Validation of community recovery algorithms is critical and requires data procurement and supporting field studies. The metrology and approaches being developed in CoE research are intended to be completely general. One of the novel tasks associated with the CoE is the joint engineering-social science field studies conducted on the impact of flood hazard following Hurricane Mathew in 2016 as fully integrated interdisciplinary teams, where field methods were developed to address research questions cutting across various disciplines. Such field studies are intended to inform models developed by the CoE, including those that predict *impacts* (i.e., physical damage and loss of social functions), household dislocation and displacement, and those that predict *recovery trajectories* at the individual, household, and community level.

A CoE/NIST team traveled to Lumberton, North Carolina in late 2016 to assess the consequences and impacts of Hurricane Matthew on that community. Specifically, the team assessed building damage, surveyed a representative sample of households to document their dislocation and early recovery efforts, met with community leaders, infrastructure stakeholders, and public officials to discuss overall impacts and recovery decisions and issues. The team returned to Lumberton in early 2018 to follow up on recovery trajectories, and to initiate a business recovery survey, and there are plans to return regularly as part of a longitudinal study. These types of longitudinal field studies, where observations are collected for the same cases (e.g., buildings, households, organizations) over time, inform recovery modeling in the IN-CORE (and other community resilience models) modeling environment. Analyzing these data independently and in conjunction with other sectors within the physical infrastructure has allowed the team to better understand and explain interdependency challenges in hazard recovery and community resilience.

These field efforts were made possible through the development of an Institutional Review Board (IRB) protocol and by securing IRB Authorization Agreements (IAA's). The IRB protocol addressed the research design, including sampling, survey respondent and interviewee identification, and participant protection. The institutional IAA's helped bring together many researchers, with a wide range of academic affiliations, under one umbrella IRB protocol. As part of the IRB process, the team developed survey instruments and interview protocols for review and that could be used for other field studies.

The CoE is also working to create a living glossary in an open-source Wiki format. The purpose of the *CoE Glossary* is to ensure that researchers are using common definitions across disciplines and tasks, connecting work to existing peer-reviewed literature, and capturing new conceptual, theoretical, and empirical contributions with the appropriate context. Ultimately, this glossary will support the usability of IN-CORE by other researchers and community stakeholders.

Closure and Next Steps for the Center of Excellence

This paper offered a brief summary of CoE activities and the development of IN-CORE and explained how testbeds and field studies focused on a range of natural hazards have augmented the measurement science undergirding the CoE. More information about the project, data sources, and associated publications can be found on the CoE website at resilience.colostate.edu. The focus of the CoE now is turning to recovery modeling with the ultimate goal of informing the development of efficient decision support algorithms to support community resilience planning. IN-CORE is scheduled to be released as an open-source computational environment at the end of December, 2019 as the CoE continues the development of this research environment by advancing the science of community resilience, with a key focus on supporting decisions and implementation.

Acknowledgments

Funding for this study was provided as part of Cooperative Agreement 70NANB15H044 between the National Institute of Standards and Technology (NIST) and Colorado State University. The content expressed in this paper are the views of the authors and do not necessarily represent the opinions or views of NIST or the U.S Department of Commerce. Additionally, the authors acknowledge the numerous researchers and students working on behalf of the CoE; a full listing can be found at: http://resilience.colostate.edu/researchers.shtml.

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