INTEGRATING HOUSEHOLD DECISIONS IN QUANTIFYING THE SEISMIC RESILIENCE OF COMMUNITIES

O.A. Sediek (1), S. El-Tawil (2), J.P. McCormick(3)

(1) *Ph.D. Student, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109, USA; email: osediek@umich.edu*

(2) *Professor, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109, USA; email: eltawil@umich.edu*

(2) *Associate Professor, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109, USA; email: jpmccorm@umich.edu*

Abstract

Recovery of communities from earthquakes is influenced by many factors beyond the physical damage of the buildings. One of those factors is the decision made by households whether to stay or abandon communities after a seismic event. This paper introduces a distributed computing framework that integrates the household decision making process with the recovery of communities from earthquakes. The decisions made by households after earthquakes are evaluated based on a set of structural, economic and social attributes. A Simple Multi-Attribute Rating Technique (SMART) is used to model post-earthquake household decision making at the building level within the frames work. The proposed framework entails the interaction between models from different disciplines through a distributed computing platform developed at the University of Michigan. The proposed framework is demonstrated through a case study focused on modeling the seismic resilience of a virtual community that comprises households with different socio-economic characteristics to simulate a typical small U.S. community. The proposed framework can help decision makers quantify the effect of different pre- and post-earthquake mitigation strategies on the performance of communities after earthquakes.

Keywords: household decision modeling, community resilience, disaster interdependencies, distributed simulation

1. Introduction

Destructive earthquakes are not frequent events. However, they have catastrophic social and economic impact on modern communities. It takes years for communities to recover (i.e. return back to their pre-earthquake state) from such events. There are numerous examples in the literature of communities that struggled to recover from destructive earthquakes. The 2010 Haiti earthquake is one of the most recent destructive earthquakes causing more than 316,000 deaths, around 300,000 injuries, and left around 1.3 million people homeless [1]. The pre-earthquake socioeconomic conditions of Haiti severely affected its recovery capability. Due to lack of resources and preparedness for such an event, 1.3 million people were left homeless for around 10 months. The overall economic losses of this event were between 7 and 14 billion US$ representing approximately 100% to 200% of Haiti's gross annual income [1].

Communities should be prepared for such events to avoid or mitigate their catastrophic consequences. The concept of community resilience has emerged from this need. Community resilience is defined as the ability of communities to return back to their pre-disaster state in a timely manner [2]. The first step to enhance the seismic resilience of communities is to quantify it so as to be able to measure the effect of different mitigation strategies on the behavior of the community. However, quantifying the seismic resilience of communities requires rigorous modeling of their behavior from the onset of the earthquake until the end of the recovery by considering the possible interdependencies between the different systems within the communities. Typical communities consist of different social, engineering, and economic systems. Detailed simulation models are available to simulate the behavior of each system in the case of seismic events. However, the interdependency between these systems is not well simulated or understood.

One of these interdependencies is between the engineering system (i.e. buildings) and the social system (i.e. household behavior). Detailed building damage and loss estimation models are available in the literature [3,4]. However, the recovery of communities from earthquakes is influenced by many other factors beyond the physical damage of the buildings. One of these factors is the decision made by households whether to stay or abandon communities after a seismic event. Abandoning communities after seismic events can negatively affect their recovery behavior due to the reduction in the allocated federal and state disaster funds resulting from the loss in population [5]. The few available studies in this area [6-9] focused on three dimensions of the household decision making process: 1) the possible decisions that can be made by the households in the community, specifically whether the household will decide to proceed in the affected community or abandon it and move to a new community, 2) the socio-economic factors affecting each of these decisions, and 3) the decision rule used to predict such decisions.

Previous studies [6-9] showed that the common decisions made by households after natural disasters are: 1) stay and repair the house, 2) stay and demolish the house, or 3) abandon the community. These decisions are affected by many factors including: the construction age and extent of damage to the building, household income, level of engagement of the household in the community, and post-earthquake employment status of the households. The decision rules used to predict such decisions are obtained either through direct surveys distributed among the households after a disaster or through assumed numerical decision models (e.g. utility based methods, logistic regression, net present value of the building, etc.).

Most of the available studies that focused on post-disaster household decisions were not implemented into a simulation framework that could be used to quantify and potentially enhance the seismic resilience of communities. Also, the dynamic nature of the problem was not typically considered (i.e. the post-earthquake decisions were evaluated one time at the end of the earthquake without considering the new conditions during the recovery stage (e.g. delayed recovery of a building)). Motivated by these needs, this paper proposes a distributed computing framework that integrates the household decision making process with the recovery of communities from earthquakes. The decisions made by households after earthquakes are evaluated based on a set of structural, economic and social attributes. A Simple Multi-Attribute Rating Technique (SMART) [10] is used to model post-earthquake household decision making at the building level within the framework. The proposed framework is demonstrated through an illustrative example that integrates the post-earthquake household decisions into quantifying the seismic resilience of a small virtual community.

2. Distributed Computing Framework

The framework used in this research consists of a set of models/simulators each of which represents an aspect of the seismic behavior of the community from the onset of the earthquake until the final recovery after the earthquake. The proposed framework is adapted from [11,12] with modifications to integrate post-earthquake household decisions in quantifying the seismic resilience of communities. The models/simulators are connected together using a distributed platform designed and developed at the University of Michigan under Project ICoR (Interdependencies in Community Resilience project [13]).

The distributed computing scheme used in the proposed framework provides two main advantages. The first advantage emerges from its name by “distributing” the computational cost of the models as they can run on the same machine or on different machines connected through the internet. The second advantage is the modularity of the proposed framework as it works in a plug and play sense, where adding/modifying any simulator is a straightforward task. This modularity can be shown in the evolution of the proposed framework from [11] then [12] then the proposed framework herein. Generally, SRTI [14] consists of three components: the RTI server, the RTI Lib API and the client (the developed models). The output of each simulator is “published” to the SRTI server which forwards it to the simulator that is “subscribed” to this message as an input as shown in Fig. 1.

The distributed computing scheme used herein allows stepping through time with different time scales to simulate the behavior of the community during different stages of the seismic event (i.e. disaster then recovery). During the first stage (i.e. the seismic event), the active simulators (i.e. sending and receiving messages) are: *city*, *ground motion*, *structural analysis*, *building damage*, and *component damage simulators*. The next stage (i.e. seismic loss estimation) starts after reaching the last time step in the ground motion history (subscribed from the *ground motion simulator*). In this stage, the active simulators (for one time step) are: *downtime* and *repair cost simulators*. Finally, during the recovery stage, the active simulators are: *household decision* and *physical recovery simulators*. The *city simulator* broadcasts the information about the studied community to all of the other simulators in the framework at the first time step in the initial stage of the simulation then shuts down to minimize the computational cost of the framework. The implementation of each simulator in the framework, except for the *household decision simulator*, which is described later, can be found in [11, 12].

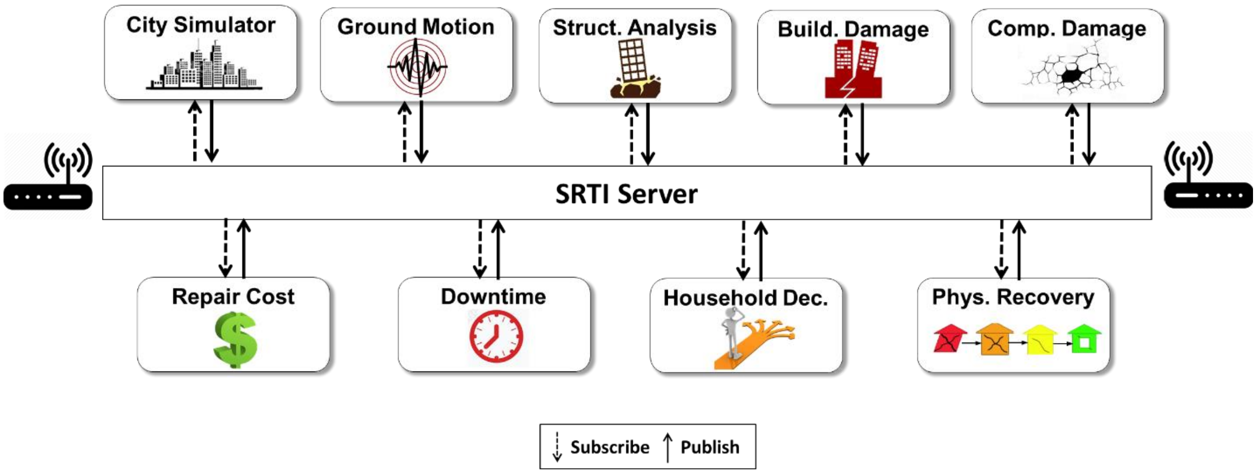


Fig. 1 – Proposed framework adapted from [11, 12] (with modifications)

3. Modeling Post-Earthquake Household Decisions

The household decision making process is modeled in the *household decision simulator* in three steps: 1) identify the possible decisions that can be made by each household in the community, 2) identify and quantify the factors that affects each decision, and 3) predict the decision made by each household in the community using a Simple Multi-Attribute Rating Technique (SMART) [10].

3.1 Possible Decisions

The possible decisions that can be made by each household in the community are: 1) stay and repair the house (i.e. do all the repairs specified in FEMA P-58 [3]), 2) stay, demolish, and rebuild the house (i.e. the downtime and repair cost of the building are set equal to the replacement time and cost, respectively), and 3) abandon the community. In the case of abandoning the community, the functionality of the house is set to zero in the *physical recovery simulator* and the community population decreases by the number of people in that house.

The household decision process is assumed to be dynamic and irreversible. Dynamic means that it is evaluated each time step during the recovery stage as the conditions change. Irreversible means that the household with decision 1 (i.e. stay and repair) can go to decision 2 (i.e. stay, demolish and rebuild) or decision 3 (abandon) as the conditions change during the recovery stage. However, the opposite cannot occur. A household with decision 3 cannot return back to either decision 1 or decision 2. The scope of the proposed methodology is single-family homes, but it can easily be extended due to the scalability of the proposed framework to include multi-family housing as well as commercial buildings.

3.2 Affecting Factors

The evaluated decision for each household in the *household decision simulator* is based on a set of structural, economic, and social factors. The structural factors are the construction age of the building subscribed from the *city simulator* and the downtime of the building subscribed from the *downtime simulator*. The economic factors are the repair cost of the building subscribed from the *repair cost simulator* and the household income subscribed from the *city simulator*. The social factors are the social interaction level of the household in the community and the length of residence in the community subscribed from the *city simulator*. The level of social interaction of the household in the community can be quantified on a scale from 0 to 100 based on the level of engagement of the household with the surrounding community.

3.3 Decision Rule

The attractiveness of a decision for a household is evaluated using the Simple Multi-Attribute Rating Technique (SMART) [10]. SMART is commonly used in decision making models due to its efficiency and simplicity in modeling human decisions. It is based on a linear additive model that consists of the sum of the performance score of each attribute "factor" affecting the household decision (X_i) multiplied by the weight of that attribute (w_i). The key idea of SMART is that the higher the total score of a specific decision, the higher the intent of the household to make that decision, and vice versa. Thus, the final decision of the household is the decision with the highest total score. This process can be represented mathematically as follows in Eq. (1):

$$U_k(t) = \sum_{i=1}^{6} w_{ik} * X_i(t) \qquad \forall\ K \epsilon \{1,2,3\} \tag{1}$$

where $U_k(t)$ is the total score for decision k at time step t, k is an index for the available decisions (1 for repair, 2 for demolish and 3 for abandon), w_{ik} is the weight that represents the effect of factor i on decision k, and $X_i(t)$ is the performance score of factor i at time step t.

The effect of the factors described earlier on different decisions is not the same for all households in the community. To account for this uncertainty, the weights of the affecting factors on different decisions, w_{ik}, are assumed to be random variables having lognormal distribution with a median of 1 and dispersion of 0.4. However, these values may be easily updated due to the scalability and adaptability of the proposed framework using data from real communities (e.g. surveys distributed among households in a community). The performance score of each factor is evaluated as follows in Eq. (2) to Eq.(4):

$$X_i = \frac{Y_i - Y_{i,min}}{Y_{i,max} - Y_{i,min}} \qquad \forall\ \ i \epsilon\ [1\ 4] \tag{2}$$

$$X_5 = \frac{Downtime}{Replacement\ Time} \tag{3}$$

$$X_6 = \frac{Repair\ Cost}{Replacement\ Cost} \tag{4}$$

where Y_i, is the value of factor i, $Y_{i,min}$ and $Y_{i,max}$ are the minimum and maximum values of factor i in the studied community, respectively.

4. Illustrative Example

The proposed framework is demonstrated through an illustrative example of a virtual district that consists of a grid of 5 x 5 residential single family homes uniformly distributed and spaced in both directions. The illustrative example is adapted from [11, 12] with modifications to account for post-earthquake household decisions. The modifications are mainly focused on the socio-economic characteristics of the households in the community. The income of each household in the community is randomized to have the same distribution as a typical U.S. middle class community. The construction age of the buildings is distributed randomly among buildings to have a distribution similar to Shelby County given in [15].

The length of residence of households in the community is also distributed randomly with a median of 13 years as stated by [16] for typical U.S communities. The social interaction of the households in the community is randomized between 0 and 100. Although the socio-economic characteristics of the households are assumed randomly, they can be collected through high fidelity surveys from real communities and plugged into the proposed framework. The layout of the illustrative example is shown in Fig. 2 where the same naming scheme in [11] is used. All of the non-structural component quantities and distributions are evaluated using the Normative Quantity Estimation Tool that is provided as part of volume 3 of FEMA P-58 [17]. The illustrative district is assumed to be subjected to the first unscaled horizontal component of the Mw 6.7 - 1994 Northridge earthquake with an epicenter in the same location as specified in [11]. Five hundred Monte Carlo simulations are used to model the different types of uncertainties (discussed earlier and in [11,12]) inherent in the proposed framework.

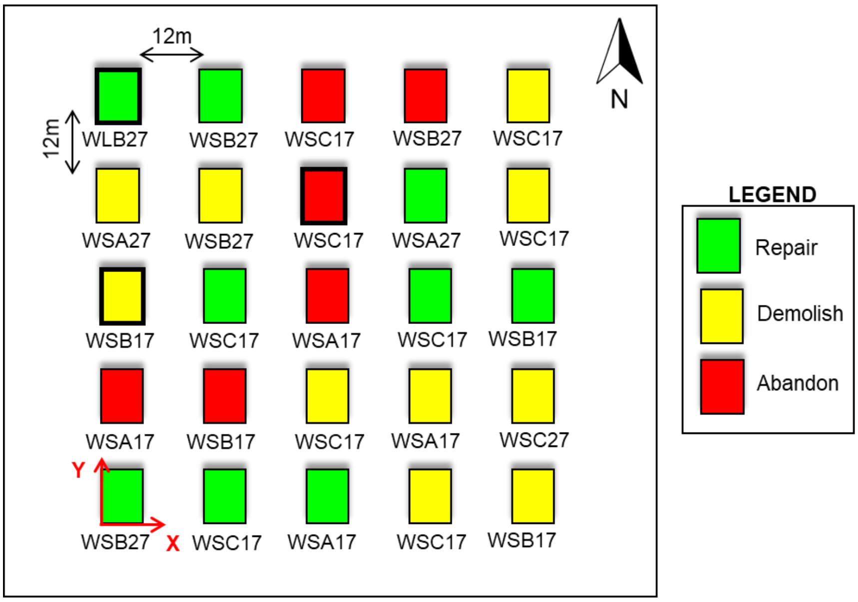
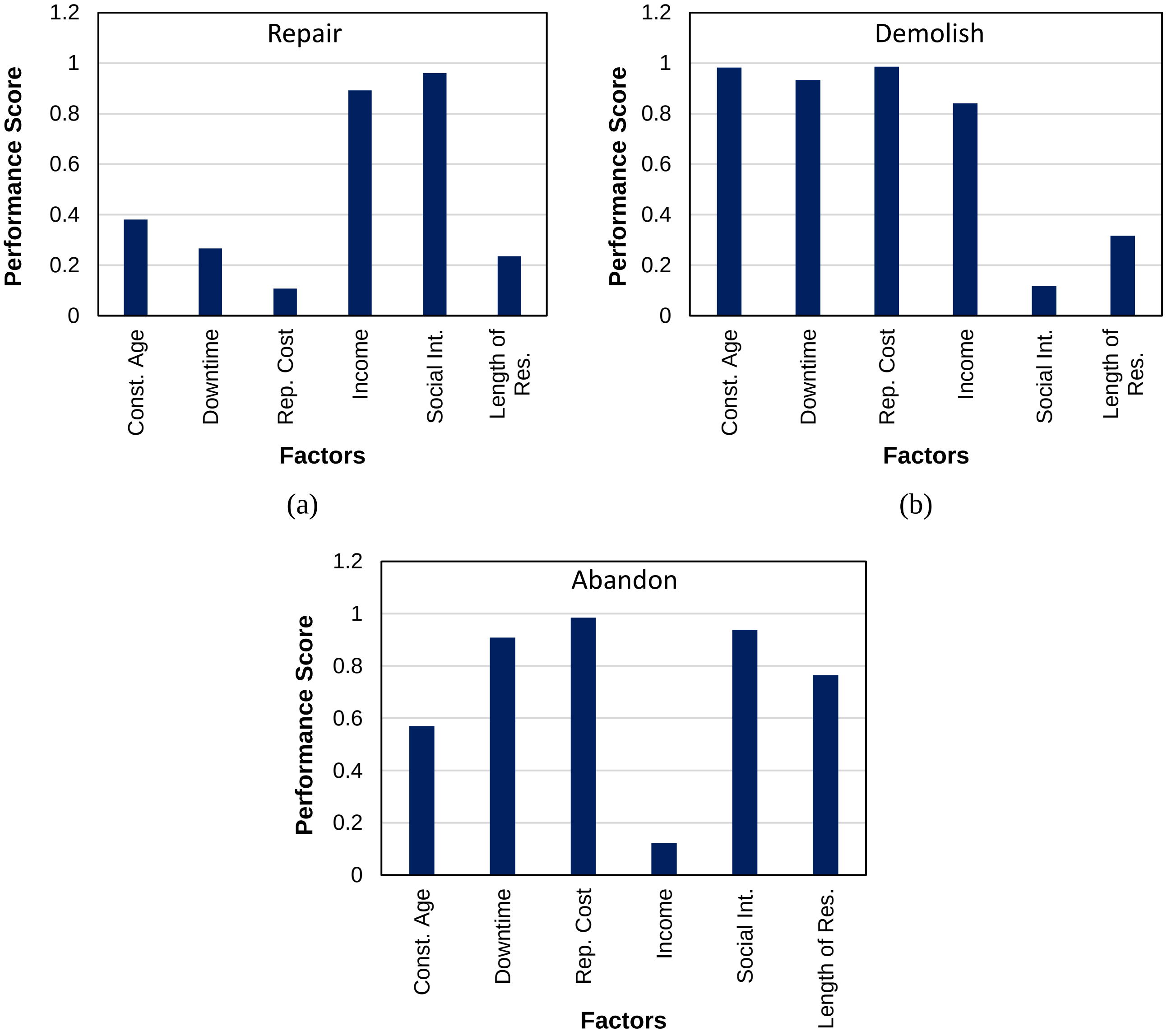


Fig. 2 – Spatial distribution of the household decisions in the studied community for one arbitrary simulation

Fig. 2 shows the spatial distribution of post-earthquake household decisions in the illustrative example for one arbitrary Monte Carlo simulation. Fig. 3 shows the performance scores for the six factors considered in the proposed decision model for three representative households with different decisions (bolded in Fig. 2) to showcase the realism of the proposed methodology and its potential to simulate the post-earthquake behavior of households in real communities. Fig. 4 shows the mean physical recovery trajectory of the demonstrated virtual district for the performed Monte Carlo simulations with and without considering post-earthquake household decisions. As shown, considering post-earthquake household decisions affected the behavior of the community in three ways: the maximum restored functionality, the time required for recovering the maximum functionality, and the resilience index ($\%R_p$) evaluated as in [12].



(a)

(b)

(c)

Fig. 3 – Performance scores of the factors affecting household decisions for representative households with : (a) repair, (b) demolish, and (c) abandon post-earthquake decisions

The studied community did not restore its full functionality after the earthquake (i.e. 100%) because of the abandoned houses. It restored approximately only 70% of its functionality on average. However, the recovery time of the community decreased from 170 weeks without considering household decisions to 140 weeks when considering household decisions (i.e. 20% reduction) for the same reason. The resilience index also decreased (shown as shaded area in Fig. 4) from 92% without considering household decisions to 70% when considering household decisions (i.e. 24% reduction). The presented results show the significance of modeling the interdependency between the social system (i.e. post-earthquake household decisions) and the engineering system of the community (i.e. buildings). Also, the presented results can help decision makers better optimize pre and post-earthquake resource allocation to enhance the seismic resilience of communities.

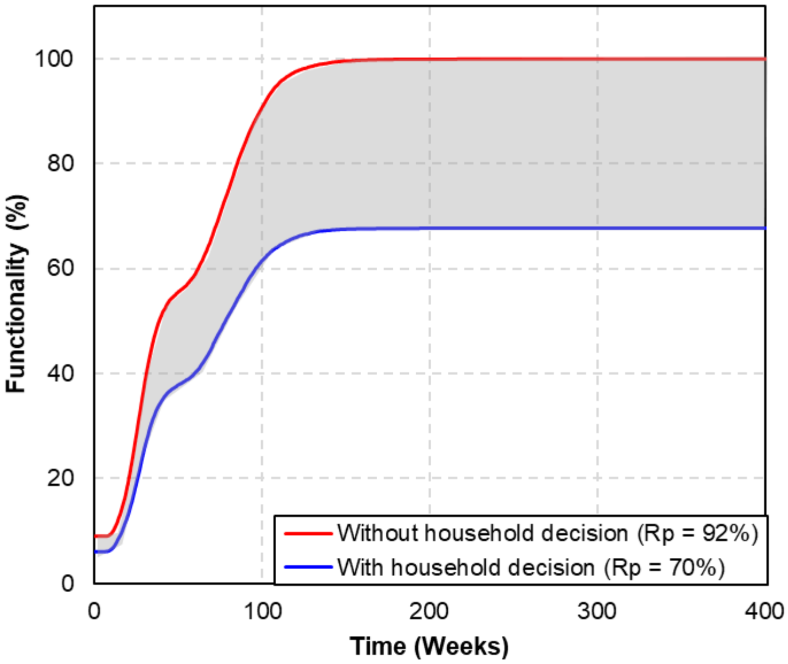


Fig. 4 – Mean recovery trajectory of the illustrative example with and without considering post-earthquake household decisions

5. Summary and Conclusions

This study proposes a distributed computing framework to integrate post-earthquake household decisions in quantifying the seismic resilience of communities. The proposed framework consists of blocks (simulators) that are independent from one another except that they are connected through a distributed computing platform developed at the University of Michigan and designed to integrate discipline-specific models in hazard simulations. This connection allows for the modularity of the proposed framework where it runs in a plug and play sense. The decisions made by households after earthquakes are evaluated based on a set of structural, economic and social attributes. A Simple Multi-Attribute Rating Technique (SMART) is used to model post-earthquake household decision making at the building level. The effect of household decisions on the recovery trajectory of the community is considered which affects the overall seismic resilience of the community. The proposed framework is demonstrated through an illustrative example of a virtual district subjected to a seismic event. The results of the illustrative example suggest that the seismic resilience of communities is significantly affected when considering the interdependency between the engineering (i.e. buildings) and the social systems (i.e. human behavior). The proposed framework also has the potential to help decision makers quantify the effect of different pre- and post-earthquake mitigation strategies on the performance of communities after earthquakes.

6. Acknowledgements

This work was supported by the University of Michigan, University of Delaware and the US National Science Foundation (NSF) through grant ACI-1638186. Any opinions, findings, conclusions, and recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsor.

7. References

[1] DesRoches R, Comerio M, Eberhard M, Mooney W, Rix GJ (2011): Overview of the 2010 Haiti Earthquake. *Earthquake Spectra*, **27** (S1), S1-S21.

[2] Bruneau, M. Reinhorn, A.M., (2007): Exploring the concept of seismic resilience for acute care facilities. *Earthquake Spectra*, **28** (1), 41–62.

[3] FEMA. (2012): Seismic performance assessment of buildings. *FEMA P58-1 Applied Technology Council, Redwood City, CA.*

[4] FEMA (2003): Earthquake loss estimation methodology: Technical manual. *National Institute of Building for the Federal Emergency Management Agency, Washington, DC.*

[5] Xiao, Y., Zandt, S. Van. (2012): Building Community Resiliency: Spatial Links between Household and Business Post-disaster Return. *Urban studies*, **49** (11), 2523–2542.

[6] Polese, M., Ludovico, M. Di, Prota, A. (2018): Post-earthquake reconstruction: A study on the factors influencing demolition decisions after 2009 L' Aquila earthquake. *Soil Dynamics and Earthquake Engineering*, **105** (April 2017), 139–149.

[7] Chandrasekhar, D., Finn, D. (2015): Influence of Household Recovery Capacity and Urgency on Post-Disaster Relocation: A Case Study of the Rockaways New York After Hurricane Sandy. *Report submitted to the Quick Response Grant Program of the Natural Hazards Center, Boulder CO*.

[8] Markhvida, M., Baker, J. W. (2018): Unification of Seismic Performance Estimation and Real Estate Investment Analysis to Model Post-Earthquake Building Repair Decisions. *Earthquake Spectra*, **34** (4), 1787–1808.

[9] Burton, H., Kang, H., Miles, S., Nejat, A., Yi, Z. (2019): A framework and case study for integrating household decision-making into post-earthquake recovery models. *International Journal of Disaster Risk Reduction*, **37** (May), 101-167.

[10] Edwards, W. (1971): Social utilities. *The Engineering Economist Summer Symposium* Series 6,119-129.

[11] Sediek, O. A., El-Tawil, S., McCormick, J. (2019): A Scalable Framework for Assessing Seismic Resilience of Communities. *Proceedings of the ASCE Structures Congress*, April 2019, Orlando, FL.

[12] Sediek, O. A., El-Tawil, S., McCormick, J. (2019): Quantifying the Seismic Resilience of Communities: A Distributed Computing Framework. *Proceedings of the International Conference in Commemoration of 20th Anniversary of the 1999 Chi-Chi Earthquake*, Taipei, Taiwan, September 15-19, 2019.

[13] ICOR (2019): Interdependencies in Community Resilience (ICOR) project. *https://icor.engin.umich.edu*/ Accessed Mar 2019

[14] SRTI (2019): Simple Real Time Interface (SRTI). *https://github.com/hlynka-a/SRTI* ,Accessed Mar 2019

[15] NCSA (2018): ERGO-EQ Platform for Multi-Hazard Assessment, Response, and Planning. National Center for Supercomputing Applications and Mid America Earthquake Center, *http://ergo.ncsa.illinois.edu/?page_id=44*, (accessed Aug 2018).

[16] Emrtath, P. (2013): Latest Calculations Show Average Buyer Expected to Stay in a Home 13 Years Special, *Special Studies, National Association of Home Builders*, January 3, 2013.

[17] FEMA. (2012): Seismic performance assessment of buildings. *FEMA P58-3 Applied Technology Council, Redwood City, CA.*