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Multi-Disciplinary Resilience Modeling for Developing Mitigation Policies in Seismic-prone Communities: Application to Salt Lake City, Utah

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ABSTRACT:

This paper presents a multi-disciplinary resilience modeling methodology to assess the vulnerability of the built environment and economic systems. This methodology can assist decision-makers with developing effective mitigation policies to improve the seismic resilience of communities. Two complementary modeling strategies are developed to examine the impacts of scenario earthquakes from engineering and economic perspectives. The engineering model is developed using a probabilistic fragility-based modeling approach and is analyzed using Monte Carlo simulations subject to seismic multi-hazard. The model accounts for shake and liquefaction and quantifies the physical damage to commercial and residential buildings at the land parcel level. The outcome of the analysis is subsequently used as input to a damage-to-functionality model to estimate the functionality of individual buildings. The economic model consists of a spatial computable general equilibrium (SCGE) model that aggregates commercial buildings into sectors for retail, manufacturing, services, etc., and aggregates residential buildings into a wide range of household groups. The SCGE model employs buildings' functionality estimates to estimate the economic losses. The outcomes of this integrated modeling consist of engineering and economic impact metrics that can be used to develop mitigation policies to help a community achieve its resilience goals. An illustrative case study of Salt Lake City, UT, is presented to demonstrate the proposed methodology.

1. INTRODUCTION

The importance of multi-disciplinary resilience modeling for developing mitigation policies in seismic-prone communities has been increasingly recognized in recent years, especially in light of events with large-scale destruction and collapse in some of the world's most seismic cities, such as the 2023 Turkey–Syria earthquake. Such damaging earthquakes can have devastating physical and economic impacts on communities. Physical damage can range from minor cracks in walls to the destruction of buildings. Economic impacts can include direct loss of money due to repairs and indirect losses due to long-term disruption of services. To mitigate these impacts, community leaders must consider various factors, including seismic hazards, building codes, and disaster planning. By understanding earthquakes' potential physical and economic impacts, communities can create effective mitigation strategies to reduce risk and improve resilience.

The structural performance of buildings during a damaging earthquake is critical for the resilience of communities, and implementing modern codes for new building construction is the most effective way to improve seismic resilience. However, for existing buildings, officials must provide various policy options to implement seismic evaluation and retrofit plans for the most vulnerable (i.e., non-code and low-code compliant) and critical buildings. For instance, in October 2015, the City of Los Angeles passed an ordinance requiring the most vulnerable buildings to be retrofitted as part of the city's Resilience by Design initiative Jones and Aho (2019). This led to 13,500 soft-story buildings with four or more residential units receiving orders to comply with the mandatory retrofits. Evaluating the effectiveness, feasibility, equity, and efficiency of policy options and retrofit plans to improve community resilience is challenging, especially when conflicting objectives exist. Due to limited funds and resources, this evaluation requires aggregating the effects of retrofitting a few buildings and connecting them to community-level resilience goals.

Previous studies (e.g., Jennings et al. (2015); Zhang and Nicholson (2016); Wang et al. (2022)) have focused on different aspects of community resilience modeling to inform decisions and have highlighted the importance of integrated multi-disciplinary approaches. However, further research is needed to develop multi-disciplinary resilience models that integrate engineering and economic systems to quantify earthquake-induced physical damages and economic losses. This research will result in modeling frameworks for comparing the benefits of various policies that can potentially reduce adverse impacts during and after a seismic event.

This paper presents a multi-disciplinary resilience modeling methodology to assess the vulnerability of the built environment and its impact on the local economy. This methodology can assist decision-makers with developing effective mitigation policies to improve the seismic resilience of communities. Another objective of this paper is to present a real-world case study of Salt Lake City (SLC), UT, developed through partnership and engagement with the city officials. This community is located near Wasatch Fault, capable of producing a $M_w 7.6$ earthquake, and is susceptible to liquefaction. It is worth noting that the economic modeling and its outcomes are briefly discussed in this paper, and readers are referred to Shields et al. (2023) for further details regarding the economic modeling and analysis of SLC case study.

2. PROPOSED METHOD OF APPROACH

This section presents the proposed method of approach for community-level seismic multi-hazard multi-disciplinary resilience modeling. Figure 1 presents an illustrative summary of implementing the proposed method of approach for the case study of Salt Lake City, UT, which will be described in the next section. The methodology consists of 1) community data collection, 2) seismic multi-hazard analysis, 3) damage and functionality analysis, and 4) economic impact analysis, 5) multi-disciplinary metrics for resilience-informed decision-making, which are discussed in detail as follows.

2.1. *Community data collection*

Collecting data and information for a community is the first step in risk and resilience modeling and informed decision-making. The devel-

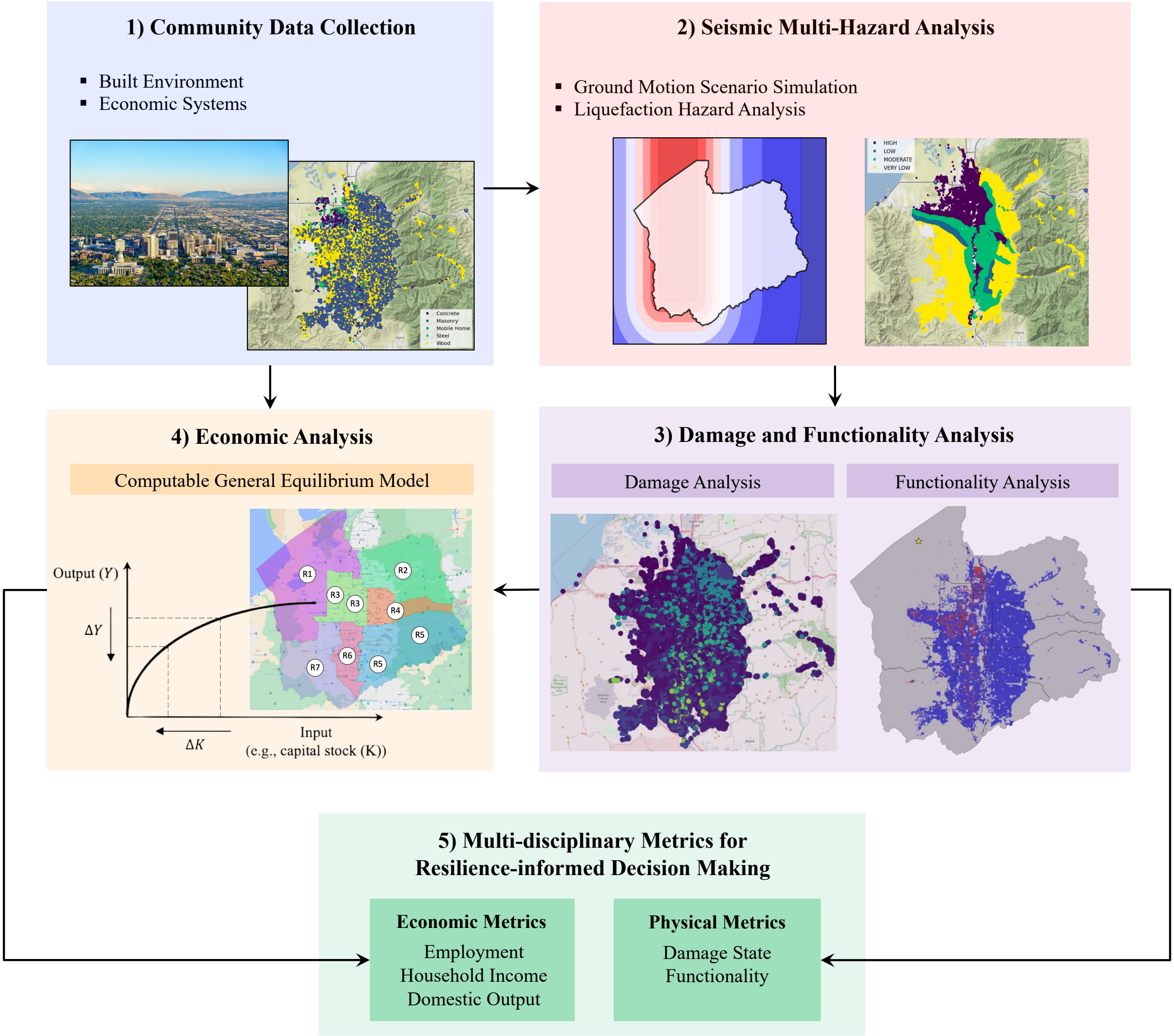

Figure 1: An illustrative summary of the proposed method of approach for multi-disciplinary seismic resilience modeling of communities with application to Salt Lake City, UT

opment of community data and information is a two-phase process. First, datasets are created by identifying appropriate risk and resilience modeling data sources. Then, a single high-rated building inventory shapefile is compiled. This inventory includes structural type, building configurations, number of stories, height, and location. Data can also be obtained from taxation databases, such as location, land value, improvement value, land use designation, tenure, year of construction, and square footage. Other attributes, such as building use, structure type, configuration, and content value, may not be directly available.

2.2. *Spatial Hazard Analysis*

The next step is to perform a seismic multi-hazard evaluation to obtain hazard intensity measures for the community of interest. This requires exploring the fault and seismic environment, liquefaction potential map, and soil dynamic properties. Scenario-based seismic hazard analysis using GMPE is used for spatial hazard modeling by considering earthquake magnitude, source-to-site distance, local soil conditions, and fault mechanism. Intensity measures include PGA, SA, PGV, and PGD. In addition, this step entails quantifying potential earth science hazards (PESH) parameters such as permanent ground deformation (PGD).

PGD is caused by liquefaction and can be evaluated by employing the available liquefaction susceptibility maps and using the HAZUS guidelines to estimate the likelihood of liquefaction for a specified susceptibility category. The probability of liquefaction, $P[L]$, for a given susceptibility category can be computed.

$$P[L] = \frac{[L|PGA = pga]}{K_M K_W} P_{ml} \tag{1}$$

where $P[L \mid PGA = pga]$ is the conditional liquefaction probability for a given susceptibility category at a specified level of PGA, P_{ml} is the proportion of the map unit susceptible, K_W is the groundwater correction factor, and K_M is the moment magnitude correction factor. For further information, readers are referred to Farahani et al. (2023).

2.3. *Physical damage and functionality analysis*

The third step is to perform fragility-based damage analysis to relate a given hazard intensity measure to the conditional probability of exceeding a certain damage state, denoted by $DS(i)$. The DSs can range from insignificant (or none) ($DS(1)$) to moderate ($DS(2)$), extensive ($DS(3)$), and complete collapse ($DS(4)$). These fragility functions are usually expressed by a lognormal cumulative distribution function defined as

$$\begin{aligned} P[ds \geq DS(i) \mid PESH] = \\ \phi\left[\frac{1}{\beta_{DS(i)}} \ln\left(\frac{PESH}{\overline{PESH}_{DS(i)}}\right)\right] \end{aligned} \tag{2}$$

where $\overline{PESH}_{DS}$ is the median value of the PESH parameter at which the structural component reaches the threshold of DS, DS. β_{DS} is the standard deviation of the natural logarithm of the PESH parameter for DS. ϕ is the standard normal cumulative distribution function. The damage analysis process should account for structural vulnerability to various PESH parameters. Therefore, the probability of exceeding each DS must be combined to account for the combined effects of PESH parameters and obtain the combined probability of exceeding a specific $DS(i)$ given by

$$\begin{aligned} &P_{\text{COMB}}[ds \geq D(i)] = \\ &1 - \prod_{j=1}^{j=m} \left(-P\left(PESH_j\right) P\left[ds \geq DS(i) \mid P_j \geq SH_j\right]\right) \end{aligned} \tag{3}$$

where j is the $PESH$ parameter index, and m is the number of PESH parameters considered in damage analysis. The combined probabilities for exceeding various DSs are given by

$$P_{\text{COMB}}[ds = DS(1)] = 1 - P_{\text{COMB}}[ds \geq DS(2)] \tag{4}$$

$$\begin{aligned} P_{COMB}[ds = DS(i)] = P_{COMB}[ds \geq DS(i)] - \\ P_{COMB}[ds \geq DS(i+1)] \end{aligned}$$

$$P_{COMB}[ds = DS(n)] = P_{COMB}[ds \geq DS(n)]$$

The combined damage estimates are subsequently used for functionality analysis. This paper defines functionality as a measure of a structural system to perform its intended functions. Full functionality is achieved when the entire system normally works to provide regular and reliable pre-earthquake services. A building is assumed to be nonfunctional if the expected value of the seismic loss ratio is greater than or equal to forty percent.

2.4. *Economic analysis*

This fours step assesses economic losses and recovery through a Spatial Computable General Equilibrium (SCGE) model. The model's key features are discussed in the following, but interested readers can find more details in Attary et al. (2020); Roohi et al. (2020). The SCGE model captures the flow of income, goods, and services, and factor payments (e.g., wages and capital payments, proprietors' income) in a regional economy and allows researchers to measure the effects of economic "shocks" and their transmission between businesses, households, and government. Thus, an SCGE model allows estimating how the degradation of building functionality affects economic variables such as business output and, consequently, the demand for production factors such as labor and local intermediate inputs.

2.5. *Multi-disciplinary Metrics for Resilience-informed decision making*

The outcomes of engineering and economic models can be employed to accurately quantify resilience metrics immediately following a simulated hazard. These metrics can then be monitored over time and analyzed in a comprehensive resilience analysis emphasizing the importance of different recovery models. The estimated impact metrics can be considered when creating mitigation policies that will help a community reach its community resilience goals. Nevertheless, this approach only considers buildings within a community and does not include any dependencies between buildings and network infrastructure, such as water and the electric power network. To tackle this limitation, future work will focus on decision-making and analyze the interdependencies between infrastructure systems and the changing variables over time. This will provide a more comprehensive view of a community's resilience and help identify the best strategies to help the community achieve its desired resilience goals.

3. CASE STUDY OF SALT LAKE CITY, UT

This section presents an illustrative case study to demonstrate the implication of the proposed methodology to Salt Lake City (SLC), UT. SLC has a population of 200,478 and is located near the Wasatch Fault, which can produce a $M_w 7.6\%$ earthquake, making it a densely populated area. SLC is susceptible to liquefaction due to its proximity to the fault line. In the event of a magnitude $M_w 7$ earthquake on the Salt Lake City segment of the Wasatch Fault, up to 2,500 fatalities and short-term economic damage of over $33 billion are expected (Pankow et al., 2015). As a result, the leaders of the city have taken proactive measures to prepare for a major earthquake, such as conducting assessments and retrofitting of vulnerable structures, including 216 residential URM structures, as part of the "Fix the Bricks" mitigation project, which has been granted a total of $3.7 million by FEMA. Also, the city is conducting assessments of critical infrastructure, such as hospitals, schools, and emergency response facilities, to identify potential vulnerabilities and develop plans to strengthen them. The city is conducting outreach and education campaigns to increase public awareness of earthquake risks and how to prepare for and respond to an earthquake. In the following, the step-by-step implementation of the proposed methodology is presented. The modeling is performed in IN-CORE, a comprehensive platform for community resilience modeling. Readers are referred to Roohi et al. (2020, 2022) for further information about the IN-CORE platform.

3.1. *Community data collection*

The methodology begins by developing geospatial datasets to characterize buildings within the SLC community. The building inventory is defined based on the SLC shapefile available on the IN-CORE data service (ID: 62fea288f5438e1f8c515ef8). This study considers all buildings, totaling 285,000. Figure 2 summarizes the distribution of attributes in the shapefile, including, but not limited to, the number of stories, occupancy type, year built, and structural type. Then, a computational model of the networked infrastructure is developed using fundamental graph theory in which components are modeled as nodes, and the connection between nodes is modeled as directed links.

3.2. *Spatial Hazard Analysis*

Seismic hazard analysis is used to simulate the impact of a large-magnitude earthquake event on the Wasatch Fault. This is a normal fault (i.e., the valley side dropping down relative to the mountainside). This study simulated an earthquake ground motion with magnitude $7.2M_W$ at the epicenter of the 2020 Salt Lake City using Boore and Atkinson (2008) GMPE to generate spatial intensity measures for the study region. Figure 3 shows the Distribution of PGA for the simulated earthquake. Figure 4 shows the liquefaction susceptibility probability map for SLC buildings.

3.3. *Physical damage and functionality analysis*

Damage analysis is performed by mapping fragility functions to each building and running a Monte Carlo simulation to estimate the probability of exceeding various DSs. The damage probabilities are subsequently used to perform functional

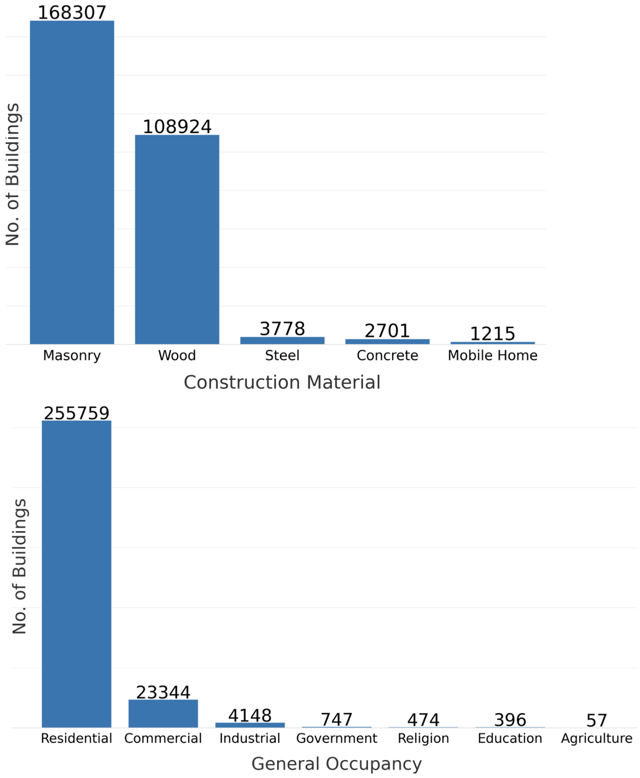

Figure 2: Distribution of SLC buildings by various building materials and construction types and use

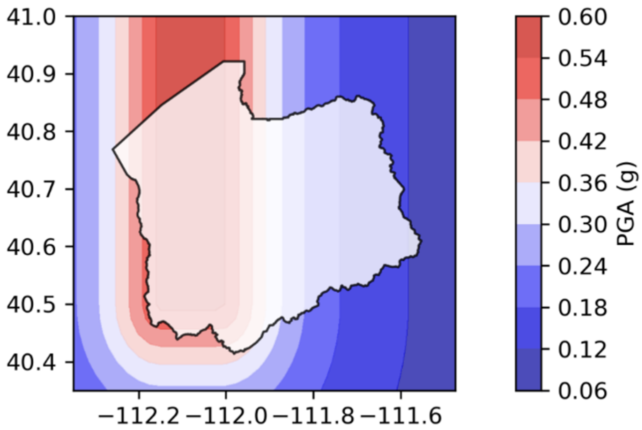

Figure 3: Distribution of PGA for the simulated M_w7.2 earthquake at the epicenter of 2020 Salt Lake City earthquake

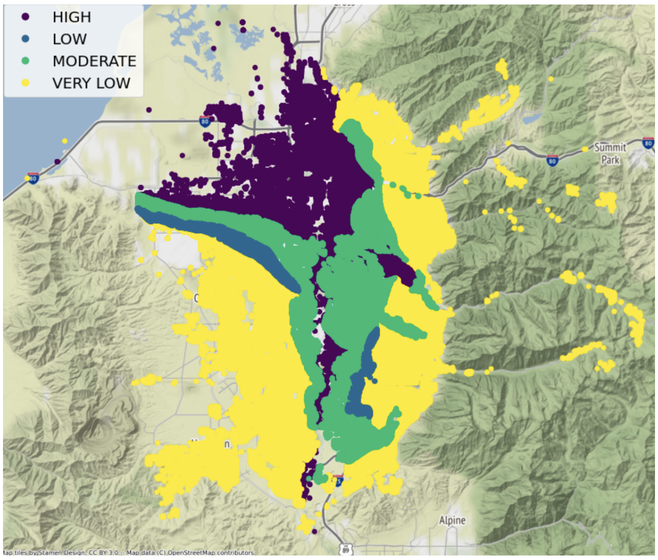

Figure 4: Liquefaction susceptibility probability map for SLC buildings

analysis and estimate the number of functional and nonfunctional buildings subject to the simulated seismic event. Functionality refers to the extent to which i) residential structures are livable and ii) commercial structures are still usable by firms to produce and/or sell their goods. Table 1 and Figure 5 present the results obtained from building functionality analysis. The analysis shows 76% of all buildings will be functional subject to the simulated $7.2M_W$ earthquake. The largest effects are on mobile homes and masonry buildings.

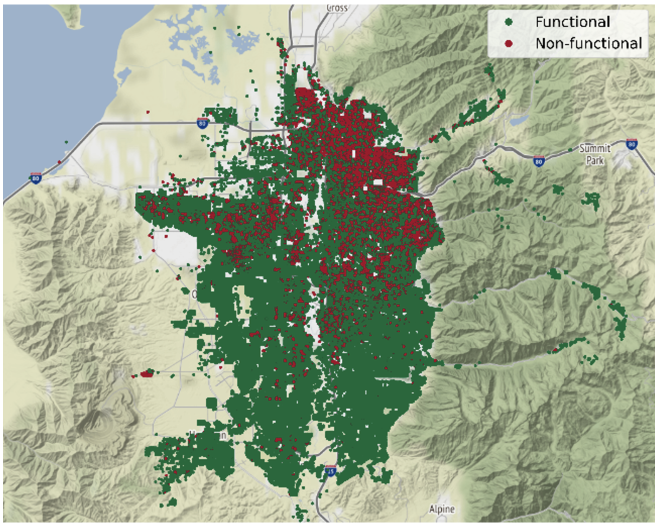

Figure 5: Distribution of functional and nonfunctional buildings subject to scenario earthquake

3.4. *Economic analysis*

The economic modeling begins with defining seven regions for the purpose of analysis, as shown in Figure 6. Region 3 (R3) hosts the central business district and is the region's economic hub. Regions 2 and 4 (and parts of 5) are largely mountainous and less populated. The functionality analysis results from the previous step were used as input to the SLC SCGE model implemented in IN-CORE. Tables 1 and 2 present the remaining percentages of physical capital still functioning in SLC after the earthquake and the lost value of the capital.

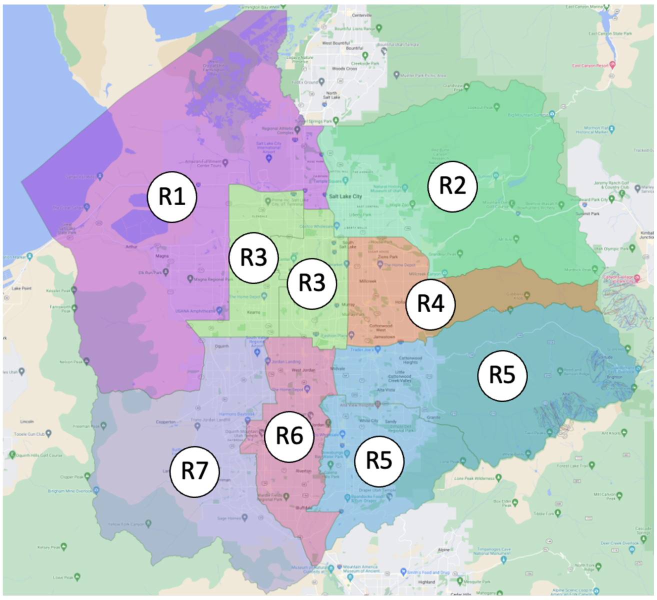

Figure 6: Disaggregated seven regions in SLC

Table 1: Engineering impacts of the earthquake: functionality for various building material types

Material Type	No. of Buildings	No. of Functional Buildings
Masonry	168,307	104,143(62%)
Wood	108,924	107,823(99%)
Steel	3,778	3,119(83%)
Concrete	2,701	2,571(95%)
Mobile Home	1,215	163(13%)
Total	284,925	217,819(76%)

Table 2: Economic impacts of the earthquake ($ losses in millions, % losses in parentheses)

Region	Variables	Simulated Impact
1	Employment	-2,162 (-3.6%)
	Domestic supply	-\$433.0 (-7.0%)
	Real household income	-\$74.0 (-3.5%)
2	Employment	-5,000 (-3.5%)
	Domestic	-\$977.5 (-5.7%)
	Real household income	-\$213.9 (-6.3%)
3	Employment	-7,893 (-4.1%)
	Domestic supply	-\$1,968.8 (-11.4%)
	Real household income	-\$734.1 (-15.9%)
4	Employment	-3,154 (-3.6%)
	Domestic supply	-\$810.7 (-7.2%)
	Real household income	-\$267.4 (-6.5%)
5	Employment	-4,685 (-3.4%)
	Domestic supply	-\$1,319.4 (-7.3%)
	Real household income	-\$412.5 (-7.3%)
6	Employment	-1,929 (-2.9%)
	Domestic supply	-\$407.2 (-4.4%)
	Real household income	-\$19.5 (-0.4%)
7	Employment	-788 (-2.9%)
	Domestic supply	-\$270.8 (-6.1%)
	Real household income	-\$41.3 (-1.2%)

3.5. *Multi-disciplinary Metrics for Resilience-informed decision making*

The outcomes of computing engineering and economic metrics from previous steps are summarized in Tables 3 and 4. Table 3 presents functionality analysis results for various building material types. The results show the number of buildings for each construction type and the percent of functional buildings subject to scenario $M_w 7.2$ earthquake. It is estimated 217,819 (76%) of the building will be functional, and the majority of nonfunctional buildings are masonry and mobile home buildings. Table 4 shows how the capital stock damages translate into economic losses in each SLC region, as estimated through the SCGE model. Overall, the estimated economic losses are \$6.187 billion in domestic supply. Note that this is smaller than the initial capital stock loss. Part of this can be explained by labor substituting for damaged capital as organizations adjust. In the longer term, declines in capital stock increase the economic return to capital, meaning new investment flows into the region, replenishing some of the damaged capital stock. Household income declines by \$1.763 billion in lost real household income, while 25,611 jobs are lost. Note that, once again, the greatest losses are in R3 and R5. The results of the SLC case study demonstrate the proposed multi-disciplinary resilience modeling methodology's capability to assess the built environment's vulnerability and its impact on the local economy. This methodology can assist decision-makers with developing effective mitigation policies to improve the seismic resilience of communities.

4. CONCLUSIONS

This paper presented a multi-disciplinary resilience modeling methodology to assess the vulnerability of the built environment and economic systems. This methodology can assist decision-makers with developing effective mitigation policies to improve the seismic resilience of communities. The proposed approach integrates engineering and economic systems to quantify earthquake-induced physical damages and economic losses, providing a modeling framework for comparing the benefits of various policies that can potentially reduce adverse impacts during and after a seismic event. The proposed methodology was illustrated by an illustrative case study of Salt Lake City (SLC), UT, developed through partnership and engagement with the city officials. The SLC case study demonstrated the potential of the proposed methodology for performing comparative multi-disciplinary seismic resilience analysis for various mitigation policy options and identifying the most effective mitigation strategies for mitigating the physical and economic impacts of earthquakes. Future research should investigate the impacts of different mitigation policies by accounting for infrastructure interdependencies and changes in resilience metrics over time to provide a more comprehensive view of a community's resilience and help identify the best strategies to help the community achieve its desired resilience goals.

5. REFERENCES

Attary, N., Cutler, H., Shields, M., and van de Lindt, J. W. (2020). "The economic effects of financial relief delays following a natural disaster." *Economic Systems Research*, 32(3), 351–377.

Boore, D. M. and Atkinson, G. M. (2008). "Ground-motion prediction equations for the average horizontal component of pga, pgv, and 5%-damped psa at spectral periods between 0.01 s and 10.0 s." *Earthquake spectra*, 24(1), 99–138.

Farahani, S., Shojaeian, A., Behnam, B., and Roohi, M. (2023). "Probabilistic seismic multi-hazard risk and restoration modeling for resilience-informed decision making in railway networks." *Sustainable and Resilient Infrastructure*, 1–22.

Jennings, E. N., van de Lindt, J. W., and Peek, L. (2015). "Multi-objective community-level seismic retrofit optimization for resiliency using engineering and socioeconomic variables." *12th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP), Vancouver, Canada.*

Jones, L. M. and Aho, M. (2019). "Resilience by design." *NAE Website*, <https://www.nae.edu/212175/Resilience-by-Design> (Jul).

Roohi, M., Li, J., and van de Lindt, J. (2022). "Multi-objective community-level seismic retrofit optimization for resiliency using engineering and socioeconomic variables." *12th National Conference in Earthquake Engineering (12NCEE), Salt Lake City, UT.*

Roohi, M., van de Lindt, J. W., Rosenheim, N., Hu, Y., and Cutler, H. (2020). "Implication of building inventory accuracy on physical and socio-economic resilience metrics for informed decision-making in natural hazards." *Structure and infrastructure engineering*, 17(4), 534–554.

Shields, M., Cutler, H., Jeon, H., Roohi, M., Nguyen, T., and van de Lindt, J. W. (2023). "Integrating stochastic engineering with economic models to evaluate earthquake mitigation strategies in salt lake city, utah." *14th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP), Dublin, Ireland.*

Wang, W. L., van De Lindt, J. W., Hartman, B., Cutler, H., Kruse, J. L., McAllister, T. P., and Hamideh, S. (2022). "Determination of individual building performance targets to achieve community-level social and economic resilience metrics." *Journal of Structural Engineering*, 148(5), 04022045.

Zhang, W. and Nicholson, C. (2016). "A multi-objective optimization model for retrofit strategies to mitigate direct economic loss and population dislocation." *Sustainable and Resilient Infrastructure*, 1(3-4), 123–136.