Integrating Stochastic Engineering with Economic Models to Evaluate Earthquake Mitigation Strategies in Salt Lake City, Utah

Martin Shields
Professor, Dep. of Economics, Colorado State University, Fort Collins, CO 80521 USA

Harvey Cutler
Professor, Dep. of Economics, Colorado State University, Fort Collins, CO 80521 USA

Hwayoung Jeon
Postdoc, Dep. of Economics, Colorado State University, Fort Collins, CO 80521 USA

Milad Roohi
Assistant Professor, Durham School of Architectural Engineering and Construction, University of Nebraska–Lincoln, Omaha, NE, 68182 USA

Tu Nguyen
Postdoc, Dep. of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80521 USA

John W. van de Lindt
Harold H. Short Endowed Chair Professor, Dep. of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80521 USA

ABSTRACT: We integrate a stochastic engineering model and an economic impact model to evaluate earthquake mitigation policies in Salt Lake County, Utah, USA. We demonstrate how earthquake-induced economic losses can vary across both economic sectors and household groups (distinguished by income), providing a framework for comparing benefits of a variety of ex-ante and ex-post policies that can potentially reduce adverse impacts during and after a seismic event. Drawing on the county assessor's data, our models are founded at the parcel level to understand how a simulated earthquake affects commercial and residential building functionality. The engineering model quantifies the physical impacts of scenario earthquakes, including the functionality of individual building structures within the community (detailed in a companion paper). The spatial computable general equilibrium (SCGE) model aggregates commercial buildings into sectors for retail, manufacturing, services, etc., and aggregates residential buildings into various household income groups. The SCGE model employs the functionality estimates from engineering analysis to estimate the economic losses. The physical and economic impact estimates for each scenario earthquake are considered baseline scenarios, setting the stage to evaluate various potential mitigation policies in terms of their ability to minimize the baseline physical and economic losses. Although this paper focuses on physical and economic losses, the modeling framework can consider other objectives, including reduced population disruption and maintaining the functionality of critical public institutions.

1. INTRODUCTION

A recent study estimates annualized economic losses due to earthquakes in the US may total more than \$6.6 billion (Jaiswal et al. 2017). Although the probability and magnitude of seismic risk has not changed much in at-risk regions, potential economic damages associated with seismic events have increased over time, due largely to growth in earthquake-prone areas and the vulnerability of older building stock.

In the US, federal, state, and local governments have a variety of policy and design options that can mitigate an earthquake's potential building and infrastructure damages, including the adoption of seismic design codes, new construction materials and techniques, and land use policy changes. These options are often costly, however, and the necessary funding and political will are often in short supply. Thus, effective community planning for earthquake resiliency requires a comprehensive benefit-cost analysis. Such analyses must consider the costs and other impediments of adopting various pre-event mitigation strategies and their relative effectiveness (i.e., the value of averted losses). It is also important to have an accounting of losses and reconstruction costs absent any action.

In this paper we estimate the economic impacts of a series of simulated earthquakes for Salt Lake County Utah, USA. Our analysis establishes a baseline understanding of potential sectoral and distributional impacts, which can help decisionmakers prioritize policies that can potentially reduce some of the adverse impacts, both during and after the event. Our multi-disciplinary team integrates two complementary modeling strategies, allowing us to examine the earthquake's impacts from both a physical infrastructure and economic perspective. For the first model, the team's civil engineers provide spatially explicit residential and commercial building and infrastructure damage and functionality estimates in the wake of a series of simulated earthquakes. For the second strategy, the team's economists link the outputs from the physical models with a spatial computable general equilibrium (SCGE) model of the region's economy. This linkage is facilitated by an inventory of key infrastructure nodes, and every building and its economic use in the study area. Through the SCGE model's production functions, [1] we estimate how losses to infrastructure and building functionality translate into losses in regional economic activity, including output, employment, and household income. Although our focus is on economic losses, the modeling framework is flexible enough to consider other objectives, including reduced population disruption and maintaining functionality of critical public institutions.

2. THE INTEGRATED ENGINEERING/ECONOMIC MODEL

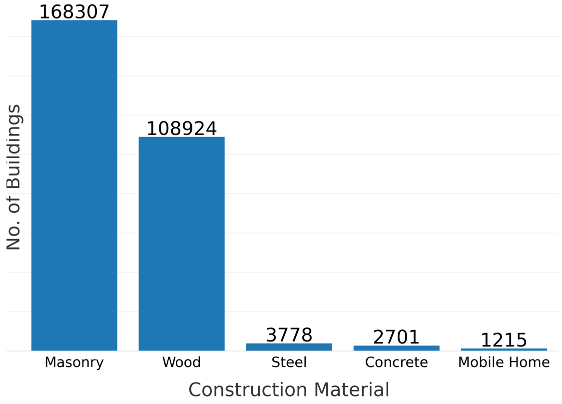
Our model is built for Salt Lake City (SLC), Utah, USA city home to slightly more than 200,000 people n 2022. SLC is located along the Wasatch Fault, which stretches 380 kilometers from southern Idaho to central Utah. SLC is close to the epicenter of the 2020 Salt Lake City earthquake, a magnitude 5.7 event, with no injuries or deaths reported and little structural damage. Geologic studies show the fault is composed of 10 individual fault segments. Each segment can generate a large magnitude earthquake for the central most active part of the fault, which includes five individual segments between Nephi and Brigham City. Historically, major earthquakes (i.e., greater than 7.0) along the fault line have occurred every 900 to 1,300 years. New fault maps show that Utah can have seismic activity in unexpected areas. The Wasatch Fault has the capability of producing a 7.6 magnitude earthquake, in which the surface rupture could cause significant damage to homes, schools, businesses, and other buildings and infrastructure. It is estimated that a magnitude 7 earthquake on the Salt Lake City segment (SLCS) of the Wasatch Fault could cause up to 2,500 fatalities and a short-term economic damage of over $33 billion (Pankow et al. 2020). Community leaders are aware of the risk and have undertaken a variety of mitigation and other preparation efforts. For example, many key structures have undergone seismic retrofitting, and federal funds have been used to upgrade unreinforced masonry buildings.

---

[1] A production function is a mathematical representation of how firms translate inputs (e.g., labor and capital) into outputs.

2.1. Engineering model

The engineering model is developed for building structures within SLC to simulate the impacts of a 7.2Mw seismic event. The modeling approach consists of 1) data and information of building inventory, 2) community model development, 3) spatial hazard analysis, and 4) physical damage and functionality analysis. The modeling is performed in the Interdependent Networked Community Resilience Modeling Environment (IN-CORE) (refer to Roohi et al. 2021, 2022 for further information). 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 1 summarizes the distribution of attributes in the shapefile, including, but not limited to, the number of stories, the occupancy type, the year built, and the structural type. Subsequently, 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 are modeled as directed links.



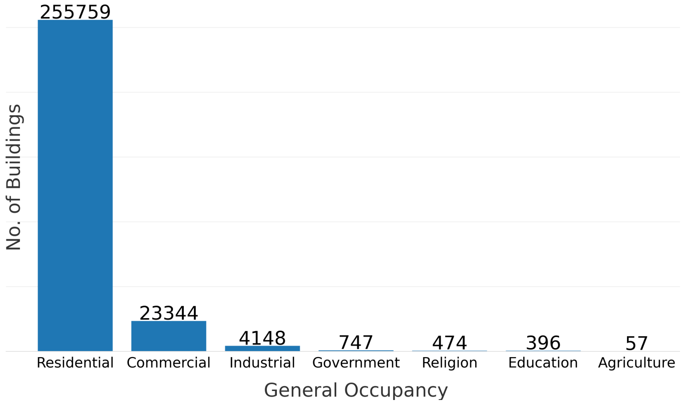


Figure 1. Distribution of SLC buildings by various building material and construction type and use

Seismic hazard analysis is used to simulate the impact of a large magnitude earthquake event in the Wasatch Fault. This is a normal fault (i.e., the valley side dropping down relative to the mountainside). We simulate earthquake ground motion with magnitude $7.2M_W$ at the epicenter of the 2020 Salt Lake City using ground motion prediction models (GMPE) to generate spatial intensity measures for the study region and used to perform damage analysis to obtain building-level damage probability estimates subject to a scenario earthquake. Figure 2 shows the distribution of peak ground acceleration for simulated Mw7.2 earthquake at the epicenter of 2020 Salt Lake City earthquake

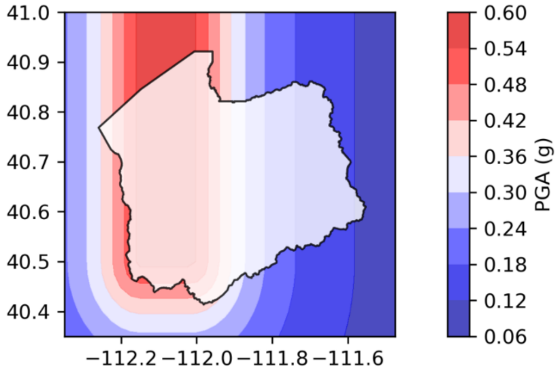


Figure 2. Distribution of peak ground acceleration for simulated Mw7.2 earthquake at the epicenter of 2020 Salt Lake City earthquake

Damage analysis is performed by mapping fragility functions to each building and running a Monte Carlo simulation to estimate the probability of exceeding various damage states. The damage probabilities are subsequently used to perform functionality analysis and estimate the number of functional and non-functional buildings subject to the simulated seismic event. Functionality refers to the extent to which 1) residential structures are livable, and 2) commercial structures are still usable by firms to produce and/or sell their goods. Table 1 and Figure 3 present the results obtained from building functionality analysis. The analysis shows 76% of all buildings will be functional subject to the simulated 7.2 M_W earthquake. The largest effects are on mobile homes and masonry buildings.

Table 1: Functionality analysis results for various building material types

Material Type	# of Buildings	# of Functional Buildings	Percent Functional
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%

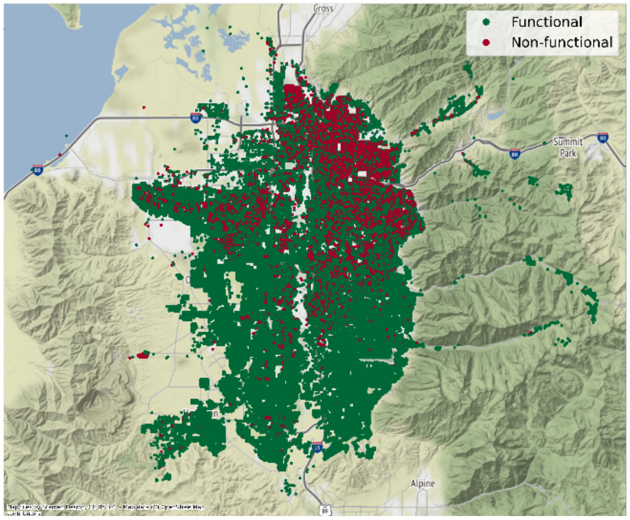


Figure 3: Distribution of functional and non-functional buildings subject to scenario seismic event

2.2. Economic model

We estimate economic losses and recovery via a SCGE model built specifically for SLC. The basics of the SCGE model are described in Attary et al (2020), but we highlight key attributes here. A SCGE model captures the flow of income, goods and services and factor payments (e.g., wage and capital payments, proprietors' income) in a regional economy, and allows analysts to determine the magnitude of adverse economic "shocks" and how these effects are transmitted between businesses, households, and government. Accordingly, our SCGE model allows us to translate how degradation of building functionality translates into adverse effects on important economic variables such as business output, and subsequently demand for production factors such as labor and locally produced intermediate inputs.

Physical capital stock is the linkage between the SCGE and engineering models. In our economic model, a firm uses labor and capital to produce goods and services, which we represent via the generalized production function:

$$Y = A * F(K, L, X) \tag{1}$$

where Y represents the value of a firm's output (in dollars), K is the firm's capital stock (e.g., building, machines, and other equipment), L is the firm's labor, and A is a productivity factor. We assume $F'(K) > 0$ and $F'(L) > 0$, while $F''(K) < 0$ and $F''(L) < 0$. It is important to recognize that local households own both labor and capital; thus, any factor payments (e.g., wages and interest income) accrue to households, which use this money to buy goods and services, many of which are produced and/or provided locally. Firms also purchase intermediate inputs (X) (e.g., electricity and raw materials), which may or may not be produced locally. When intermediate inputs are produced locally, the same production logic applies to those firms.

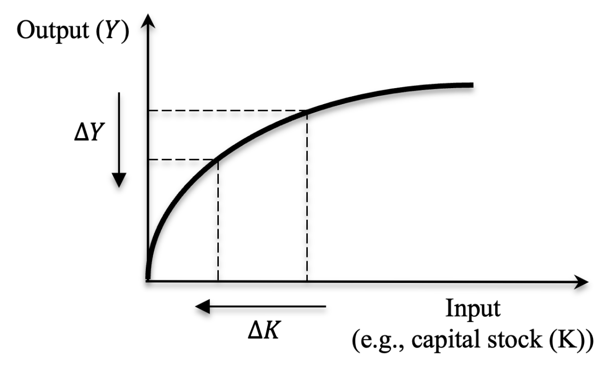


Figure 4: Production function and capital stock losses

Figure 4 shows illustrates the association between capital and output in a production function with diminishing marginal product in a single input. Losses to capital stock from the earthquake are represented by ΔK, with subsequent losses in output represented by ΔY. Because output is negatively impacted, it is also likely that employment losses will follow, as fewer workers will be needed.[2] Important concomitant impacts are losses in wage and capital income to households, and reductions in intermediate input demand. In other words, capital stock losses adversely impact the economy through multiple channels.

The magnitude of output loss is determined by the size of the capital stock loss. In this paper we set the baseline for examining how various mitigation strategies can reduce the size of these losses. Follow on research will look at how alternative mitigation strategies affect ΔK (i.e., the benefits), relative to a "do nothing" case. When affixing costs to the alternative mitigation strategies, we can get a sense of benefits versus costs.

In Figure 5 we show the seven regions we consider in our analysis. 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, hence less populated.

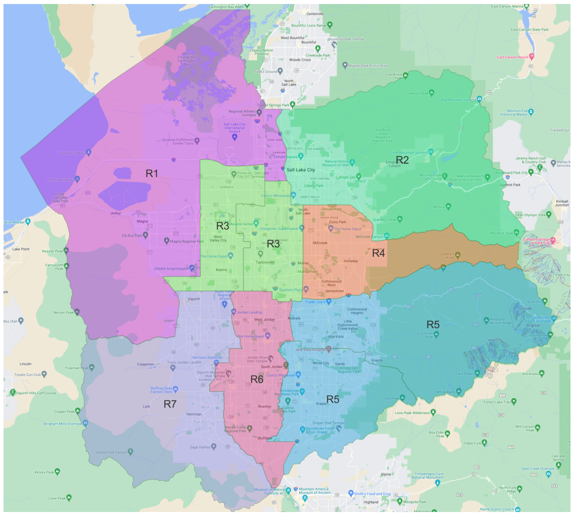


Figure 5. Disaggregated seven regions in SLC

3. SIMULATIONS AND RESULTS

We simulate the earthquake's damages to SLC's commercial and residential building stocks using the previously described method. Tables 2 and 3 present the remaining percentages of physical capital that are still functioning in SLC after the earthquake as well as the lost value of the capital.[3] Table 2 delineates the damages into a variety of economic sectors. Total capital stock and subsequent damage estimates are derived by aggregating parcel level data that includes the economic use of each structure. We aggregate residential sectors according to two housing types. HS1 includes most single-family homes, while HS2 includes mobile homes and multi-family units. In SLC, lower income households are largely in HS1.

---

[2] When capital is lost, firms will sometimes hire more workers to substitute for the lost capital, somewhat offsetting the total loss in production capabilities; in practice, though, lower levels of output still tend to reduce total labor demand.

[3] The value of capital stock is based on Salt Lake County assessor's data, which provides estimates of the value of each building (https://slco.org/assessor/). Because we are unable to obtain reliable information on physical content for these structures, we just damaged building capital.

Table 2. Estimated damage to capital stock, by sector

Sector	Remaining capital stock functioning (%)	Value of capital stock loss (mil of $)
Agriculture, Mining	93.8%	0.2
Art, Accommodation	87.7%	356.7
Other Commercial	85.9%	2,419.2
Construction	92.6%	25.1
Education	94.6%	83.0
Health	85.4%	158.8
Manufacturing	96.4%	136.9
Religious	92.6%	99.8
Utility	79.7%	107.5
HS1 (single)	77.3%	6,275.6
HS2 (mobile, multi)	84.0%	1,221.4
Total		10,884.2

Overall, the capital stock losses from the simulated earthquake total $10.884 billion. Looking at industry impacts, the greatest losses occur in “Other Commercial” ($2.419 billion), an aggregation of 10 NAICS super-sectors.[4] The bulk of the damages, however, affect housing. We estimate $6.275 billion in damages to HS1, representing a 22.7 percent decline. HS2 suffers a 16 percent decline ($1.221 billion).

Table 3 provides estimated capital stock losses for each region. R3 bears the brunt of the damages, suffering $3.464 billion in capital stock losses. This is unsurprising given the region is home to a larger share of overall regional economic activity.

Table 3. Estimated total capital stock losses, by region

Region	Remaining capital stock functioning (%)	Value of capital stock loss (mil of $)
Region 1	83.5%	$786.9
Region 2	87.3%	1,797.1
Region 3	79.4%	3,464.5
Region 4	93.6%	1,253.8
Region 5	85.0%	2,626.4
Region 6	90.4%	555.2
Region 7	93.0%	400.2
Total		10,884.2

Table 4. Impacts of the earthquake ($ losses in millions, % losses in parentheses)

Variables	Simulation: Impact of earthquake
Region 1	
Employment	-2,162 (-3.6%)
Domestic supply	-$433.0 (-7.0%)
Real household income	-$74.0 (-3.5%)
Region 2	
Employment	-5,000 (-3.5%)
Domestic	-$977.5 (-5.7%)
Real household income	-$213.9 (-6.3%)
Region 3	
Employment	-7,893 (-4.1%)
Domestic supply	-$1,968.8 (-11.4%)
Real household income	-$734.1 (-15.9%)
Region 4	
Employment	-3,154 (-3.6%)
Domestic supply	-$810.7 (-7.2%)
Real household income	-$267.4 (-6.5%)

---

[4] These sectors include Wholesale and Retail Trade Transportation and Warehousing, Information, Finance and Insurance, Real Estate and Rental and Leasing, Professional, Scientific, and Technical Services, Management of Companies and Enterprises, Administrative and Support and Waste Management and Remediation Services, and Other Services (except Public Administration).

Region 5	
Employment	-4,685 (-3.4%)
Domestic supply	-$1,319.4 (-7.3%)
Real household income	-$412.5 (-7.3%)
Region 6	
Employment	-1,929 (-2.9%)
Domestic supply	-$407.2 (-4.4%)
Real household income	-$19.5 (-0.4%)
Region 7	
Employment	-788 (-2.9%)
Domestic supply	-$270.8 (-6.1%)
Real household income	-$41.3 (-1.2%)

In Table 4 we show how the capital stock damages translate into economic losses in each 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.

4. DISCUSSION

Table 4 presents a baseline estimate of the economic damages of the simulated earthquake. These results show that the central business district is the most vulnerable geographically, while residential housing is the most vulnerably, economically. Together, these findings can shed light on potential targeted mitigation policies. For example, the building stock for various occupancy types and their estimated functionality can be investigated using an engineering model. Analysis can be performed to identify the cost and effectiveness of various seismic retrofit strategies in improving engineering and economic resilience metrics. If the objective is to improve seismic resilience of residential buildings, retrofitting the vulnerable structures, such as unreinforced masonry buildings and mobile homes, is essential for ensuring their structural integrity and safety. There are a number of approaches to retrofitting unreinforced masonry and mobile homes, including strengthening the walls, floors, roof, and foundation, and adding bracing. Iterative seismic resilience modeling can be performed to evaluating the effectiveness, feasibility, and efficiency of policy options and retrofit plans to improve community resilience and identify effective and optimized mitigation policies.

5. CONCLUSIONS

This paper presents an integrated engineering and economic model to examine potential economic losses (e.g., employment,) resulting from a simulated earthquake in Salt Lake City, UT. Our model demonstrates that such losses vary across both physical and economic systems, with housing particularly vulnerable. Through the comparison of results under various mitigation policies, this model is capable of assisting policy makers with the vital information required to make informed decisions based on cost-benefit analysis. This is of particular significance, as it enables decision makers to assess the potential economic implications of policy implementations and their associated costs.

6. REFERENCES

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

Jaiswal, K., D. Bausch, J. Rozelle, J. Holub, and S. McGowan. 2017. *Hazus® estimated annualized earthquake losses for the United States*. Federal Emergency Management Agency.

Pankow, K. L., J. Rusho, J. C. Pechmann, J. M. Hale, K. Whidden, R. Sumsion, J. Holt, M. Mesimeri, D. Wells, and K. D. Koper.

2020. “Responding to the 2020 Magna, Utah, Earthquake Sequence during the COVID-19 Pandemic Shutdown.” *Seismological Research Letters*, 92 (1): 6–16. https://doi.org/10.1785/0220200265.

Roohi, M., J. Li, and J. Lindt. 2022. “Seismic Functionality Analysis of Interdependent Buildings and Lifeline Systems.” Salt Lake City, UT, USA.

Roohi, M., J. W. van de Lindt, N. Rosenheim, Y. Hu, and H. Cutler. 2021. “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): 1–21. https://doi.org/10.1080/15732479.2020.1845753.