The Effect of Scientific and Socioeconomic Uncertainty on a Natural Hazards Policy Choice

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EXTENDED ABSTRACT

Policy decisions regarding the mitigation of natural hazards are made by individuals, businesses, and public agencies. Resources are rarely sufficient to satisfy full protection and tradeoffs are usually necessary. Choices are affected by external policies including subsidies and regulations. Choices affect the vulnerability of particular locations and have consequences for a whole community that include negative and positive effects on property values; legislation such as the Alquist-Priolo Hazard Zonation Program to delineate hazard zones in California can have a negative effect, and subsidized insurance policies such as in the US National Flood Insurance Program can over value properties in a flood plain.

The USGS is developing tools for quantitative policy analysis. The Land Use Portfolio Model (LUPM) is a GIS-based modelling, mapping, and risk communication tool designed to assist communities in understanding and reducing natural-hazards vulnerability and in making loss reduction investment decisions. Memphis, Tennessee was chosen as a test site to evaluate the usefulness of the model to local planning authorities, emergency managers, and businesses in evaluating the economic consequences of an earthquake mitigation strategy. Memphis, like many urban areas around the world, is subject to the damaging effects of earthquakes that are unevenly distributed across the region. This paper reports on the application of the LUPM and related studies to evaluate the economic effects of different sources of uncertainty on a policy decision regarding future earthquake hazard mitigation for Memphis, TN.

Specifically, we present two examples concerned with implementing policies to increase safety and reduce property loss in the event of a large, damaging earthquake. The analysis recognizes some of the uncertainties inherent in costly hazard mitigation decisions for earthquake triggered liquefaction ground failure.

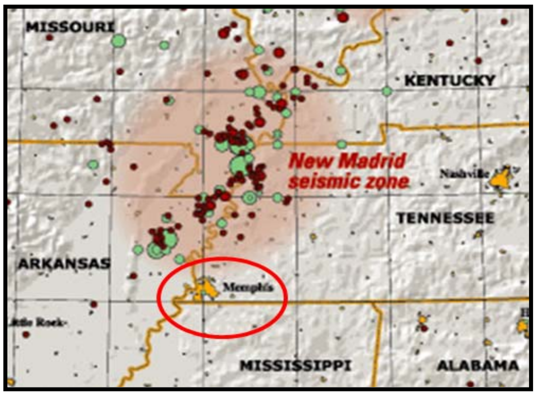
The first policy example describes an investment decision that is based on a prospective analysis of a future development scenario for a mix of commercial and industrial development with an estimated value of $9.6 billion (US). The LUPM is run with and without the implementation of a liquefaction resistant building standard. By varying building mitigation costs and alternative planning horizons, decision makers can assess the effect of these uncertainties on justifying the standard. Under different, yet equally plausible assumptions, implementing the decision can be shown to have both positive and negative returns on investment (ROI = 11.7 to 0.13, where ROI is the ratio of [losses avoided] / [mitigation costs]).

The second example considers the effects of an uncertain earthquake epicentre location, correlated ground failures, and valuation methodology on policy choice. In a residential area, it is demonstrated that these uncertainties combined can double the estimate of expected loss exceeded for a given probability and enters a range of unacceptable risk.

1. INTRODUCTION

The City of Memphis and surrounding Shelby County lie within the New Madrid Seismic Zone (Figure 1), which extends from northeast Arkansas, through southeast Missouri, western Tennessee, western Kentucky to southern Illinois. Historically, this area has been the site of some of the largest earthquakes in North America. Earthquakes with magnitudes greater than 7.0 occurred in this area between 1811 and 1812. The estimated recurrence interval of a magnitude 7.0 Earthquake is approximately 500 years (Gomberg and Schweig, 2002)

The public policy analyses are conducted at regional scale. The examples are designed to inform decisions under uncertainty about the allocation of scarce resources to reduce the risk of loss of life and property, and financial investment.



A discussion and summary follows.

Figure 1: Map of the New Madrid seismic zone showing epicentres for events occurring prior to 1974 (green circles) and between 1974 and 2002 (red circles), Earthquake magnitudes (2.5 to 8.0) are indicated by circle size. (Stover and Coffman, 1993)

2. ECONOMIC CONTEXT: PUBLIC CHOICE

We consider the case of evaluating a policy when the benefits and costs are uncertain due to uncertainty in scientific and socioeconomic information. Uncertainty affects the policy instrument choice by the decision maker (Stavins, 1996). Most analyses of this problem have been examined from the perspective of individual choice (Ehrlich and Becker, 1972, Brookshire, et. al., 1985). It is also appropriate to analyse a regional policy for earthquake hazard mitigation as a public choice problem (Lewis and Nickerson, 1989, Gollier, 2001).

2.1. Public Choice Problem

The public choice problem of investing in community earthquake hazard protection assumes a regional economy of private production, consumption and investments, and public goods (e.g., public infrastructure and safety rules). Investment in hazard mitigation involves both individual and collective decision making and can be a risky investment choice (Lewis and Nickerson, 1989). It is risky because the hazard may not occur over the productive lifetime of the mitigation investment, mitigation may be ineffective due to an event that exceeds its design standard, or the strategy may be prohibitively expensive. The outcome of the investment is uncertain; the return on the investment is uncertain. To better inform the investment choice under uncertainty, we include this decision risk in the policy choice scenario.

The question arises of how much to spend on protection and how to apportion it between private and public expenditures. Private expenditures on mitigation are voluntary and limited (Lewis and Nickerson, 1989) unless a regulation is required as a result of collective action. When a rule or standard is established, it imposes an economic cost in the form of income compensation as a transfer from society to individuals who receive the benefits. Transfers can be diverse, such as land use controls and amenities that affect the quality of life, or may offer protection from natural hazards, assistance during emergencies, and aid to recover from disasters. The number of individuals who receive benefits depends on the outcome in the adverse state of the environment. But we do not know exactly who and how many assets are in danger for any specific realization of an event. To account for this type of description of the adverse state, the policy analysis should include a range of potential outcomes to reflect the uncertainty in the information. Given the uncertainty, we utilize various risk metrics in addition to expected loss and return on investment, analogous to a risk - return decision-making criterion (Bedford and Cooke, 2001).

To assess the implications of informational uncertainty, we examine one hypothetical event, a magnitude 7.7 earthquake that triggers significant liquefaction damage. We apply the decision framework and vary a variety of input parameters (selected planning horizon, asset valuation, mitigation cost, and probabilistic earthquake source) to generate a range of probabilistic outcomes. Different ranges of outcomes can lead to alternative recommendations to solve the problem

2.2. A Portfolio Choice Model

There are a variety of ways to reduce the effects of natural hazards. Hazard mitigation measures can be site specific for individual structures or community-wide (protection of large areas). Some of these measures work better in benign situations (e.g., braced cripple walls for earthquake shaking) and others in extreme situations (e.g., automated warning systems for evacuation). The decision is to choose the combination of places and measures (i.e. portfolio of investments) to reduce hazard and investment risks.

The metric(s) used in the LUPM to compare alternatives and decide if any of the options are acceptable are the expected return on investment and the acceptable risk. We focus on scientific uncertainties, such as the earthquake source, to determine an acceptable risk threshold. The first example is a comparison of expected return on investment (ROI), an efficiency criterion (expected return and residual risk) for a given level of regulatory stringency under varying time horizons and mitigation costs. The second example illustrates the decision risk associated with spatially correlated failures and asset valuation, and effect on an acceptance criterion for a mitigation strategy that is consistent with a financial measure, *value-at-risk* (*VAR*).

The LUPM is applicable because it is able to link what scientists know about the odds and location of natural hazard occurrences, what community stakeholders express about the initial wealth values at risk (Bernknopf et. al., 2006) and what engineers say about the costs and effectiveness of mitigation alternatives to examine the return on investment. The mitigation investments are risky because they have an uncertain yield per mitigation dollar invested. The model also informs decision makers about the financial risks of mitigation options with uncertain returns given resource constraints. In summary, the LUPM provides an analysis of asset risk and return on investment (e.g., Wein et. al., 2007).

In these examples, we assume community wealth is measured as parcels of land and the buildings on them are the assets that have a reduced value after a natural hazard strikes. A lower bound on community wealth is the sum of structure replacement values and an upper bound on community wealth is the sum of total "economic" value that includes replacement value + land value.

3. EXAMPLE: POLICY ANALYSES OF EARTHQUAKE HAZARD LOSS REDUCTION IN MEMPHIS, TN

Regional losses depend on the size and extent of the potential hazard. Community vulnerability can be reduced by private investment or public sector requirements for hazard mitigation. However, loss estimates alone are not sufficient for prioritizing mitigation investments. When information about losses and hazard occurrence is combined, we can estimate the risk to the community. There is considerable decision risk inherent in uncertain predictions of the timing and size of earthquakes. In both policy examples, the selected Memphis earthquake hazard for the analysis has a probability (in 50 years) of a repeat event of magnitude 7.7 of 10% (Cramer, et. al., 2004). In both examples, losses are incurred from ground failure (liquefaction) triggered by the earthquake as shown in Figure 2.

3.1. Policy analysis with a variable planning horizon and uncertain mitigation costs

For our first example, the questions are 1) is implementation of a stringent building code in Memphis a good public policy, and 2) can the investment be justified for reducing earthquake risk? For this analysis we consider new commercial and industrial buildings. We assume there will be one earthquake during the relevant time period, that decisions makers have heterogeneous planning horizons, that mitigation is 100% effective and that mitigation costs is estimated as a % of property value.

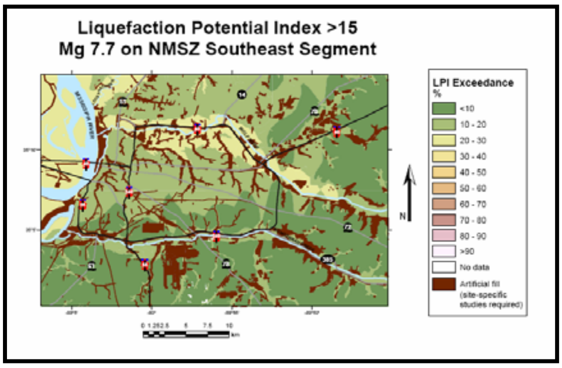


Figure 2: Probability of major liquefaction from a magnitude 7.7 earthquake (from Rix and Romero-Hudock, 2006)

An inventory of hypothetical structure types for the ~12,000 vacant parcels in Memphis was developed using the distribution of existing commercial and industrial buildings in Shelby County. In this example, asset value at risk is the sum of market value for the land plus the present value of building replacement cost. Using this value, expected loss is estimated for locations susceptible to liquefaction damage. The analysis proceeds with and without the implementation of the code. Table 1 contains the inputs and outputs of the case. We vary the probability of the hazard, time horizon, mitigation cost, and strategy based on liquefaction susceptibility categories. Output statistics are community wealth retained (sum of property values), ROI, and a measure of acceptable risk (residual risk given by the expected loss of unmitigated parcels).

We include three types of uncertainty in this case: 1. Mitigation costs have a wide variance due to differences in building type, ground conditions, engineering and construction effectiveness, expert opinion and risk aversion. 2. The planning period that is used to evaluate the mitigation investment, and 3. The likelihood of an event (increases over time).

Inspection of Table 1 suggests that all of the input variations have a significant impact on the choice. Scenario run 1 assumes no change in the standard and is the without case. This run indicates an expected loss of 26% of the value of the new building stock. In run 4, when only the highest liquefaction susceptibility classes (see Figure 2 for liquefaction categories) are included in the rule and the earthquake is certain, the code is cost effective for the mitigation cost options and should be implemented. However, while there is no standard for risk tolerance, the residual risk is \$0.8B (US). When the time period is varied and the probability of recurrence is part of the analysis, only run 6 demonstrates a positive ROI. This is due to the 50 year time period and the probability of earthquake recurrence. The analysis can be extended to additional earthquakes, earthquake source locations, secondary hazards, etc., to assess and justify investment in a safety standard.

3.2 Policy Analysis with Spatially Correlated Losses

One problem with existing site independent earthquake-loss-estimation methods is that they assume spatial independence and ignore spatially correlated losses (Smith et. al, unpublished manuscript). In this example, the investment choice involves analysis of residential structures.

We include four types of uncertainty in this example. 1. There are a large number of possible locations for earthquakes in the New Madrid zone. There is no surface fault trace. Earthquakes are assumed to be uniformly distributed in the area shown in Figure 1. Peak ground acceleration (PGA) that can cause total destruction for sites with a liquefaction hazard vary. 2. There is a high degree of uncertainty about the earthquake attenuation functions that define the mean PGA levels at each distance from the earthquake source, program benefits can vary because possible spatial correlation exists between destruction events. 3. Spatial autocorrelation is modelled in terms of a spherical covariogram. 4. What should be chosen as the asset value; structure replacement value (building replacement cost, *Blg*) is an appropriate valuation when a community returns to normal quickly and Total Economic Value (total value=building + land value, *Tot*) captures an upper bound on the loss by including community amenities that contribute to land values, when the return to normal takes longer.

Empirical and scientific evidence indicates that levels of shaking strong enough to cause liquefaction at residential sites close to one another tend to exhibit some degree of positive correlation. In a Memphis neighbourhood of more than 1,200 land parcels, we compare a spatially dependent loss estimate with a spatially independent estimate for the scenario earthquake. In addition to spatial correlation of earthquake triggered liquefaction, losses are estimated for *Blg* and *Tot*. Repeated simulation of earthquake scenarios that are defined by varying the earthquake epicentre yields a sampling distribution of total realized losses that provide maximum-likelihood estimates for an *exceedance-probability* (*EP*) function of damage. An *EP curve* specifies the probabilities that a certain level of losses will be exceeded (Kunreuther, 2003).

The model is used to examine a stylized policy decision to mitigate a neighbourhood north of the Memphis central business district that is subject to liquefaction. The assessed values are listed in Table 2. The risk analysis, illustrated in Figure 4, compares the *EP* functions for spatially independent and dependent failure for the *Blg* and *Tot* valuations. For this case, the relevant pairs of *EP* curves in Figure 4 are shown as dashed lines for building replacement values and as solid lines for total value. For example, the horizontal displacement between the two curves Blg_{SI} and Tot_{SI} represents the total land value of all sites destroyed at each level of exceedance probability under the spatial independence scenario. These horizontal intervals can be interpreted as bounding the potential damage costs at each level of exceedance probability. The objective of this example is to show that failure to account for unobserved spatial dependencies can lead to an underestimation of potential damages when losses are high, causing decision makers to believe they are better off than they actually are.

Suppose that a mitigation policy for the Memphis neighbourhood, in Figure 3, is under consideration. We use an alternative definition of acceptable risk for the community and assume that risk assessment for this earthquake mitigation decision is carried out in terms of *Value-at-Risk* estimation (a common tool used for analysis of financial risk). This assessment approach begins by identifying a relevant investment time frame, *T*, together with a relevant risk level, ρ, and then seeks to estimate the minimum loss level, $L = L(\rho, T)$, that will be exceeded with probability ρ in time period *T*. This loss *L* is then referred to as the *VaR* for the investment (relative to ρ and *T*).

Scenario Run	1	2	3	4	5	6
Inputs Exposure $Billion	2.5	2.5	2.5	2.5	2.5	2.5
Earthquake probability	1.0	1.0	0.002/yr	1.0	0.002/yr	0.002/yr
Time horizon (*T*)	1	1	20	1	20	50
% mitigated	0.0	100.0	100.0	>60% sites	>60% sites	>60% sites
Mitigation cost, $B (% of value)	0.0	0.75 (10%) 2.25 (30%)	0.75 (10%) 2.25 (30%)	0.14 (10%) 0.42 (30%)	0.14 (10%) 0.42 (30%)	0.14 (10%) 0.42 (30%)
Outputs Wealth retained, $B	7.1 (74%)	9.6 (100%)	9.6 (100%)	8.7 (91%)	9.5 (99%)	9.4 (99%)
ROI	n/a	3.27 (10%) 1.09 (30%)	0.13 (10%) 0.05 (30%)	11.7 (10%) 3.9 (30%)	0.5 (10%) 0.2 (30%)	1.2 (10%) 0.4 (30%)
Acceptable risk, $B	2.5	0.0	0.0	0.8	0.03	0.1

Table 1: LUPM Statistics for a 7.7 Earthquake (Liquefaction risk assessment: total asset value=$9.6Billion (US); n=11,976 parcels)

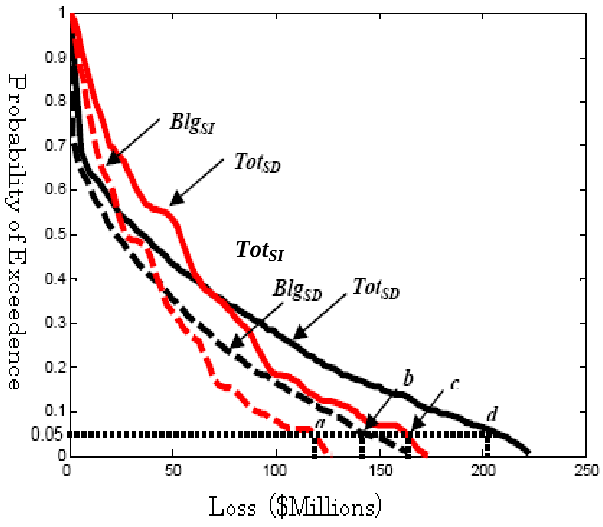
In the present context, a time frame of 50 years is assumed to be a "building lifetime." For illustration, it is convenient to choose a risk level of $\rho = .005$, i.e., of "five-in-a-thousand". Hence the relevant value at risk from earthquakes is taken to be the minimum level *L*, for which there is only a five-in-a-thousand chance of incurring losses as large as *L* within the next 50 years.

	Mean Building Value	Mean Total Value	N
Sample Site	$156.1	$221.7	5388
Memphis	$146.9	$199.8	336,652

Table 2: Assessed Value for Properties in the Study Area and for Memphis, TN

In this context, we consider a specific hazard mitigation policy for implementation that involves a subsidy for earthquake reinforcement expenditures together with a stringent liquefaction building code for new construction. The total cost of the proposed policy is assumed to be $15M (US). Also this policy will be worthwhile only if the value at risk from a major earthquake is a least ten times this amount, i.e., at least $150 million. To calculate *VaR*, we combine the exceedance probabilities that are actually conditional probabilities based on the occurrence of the 7.7 earthquake with the probability of recurrence of the earthquake. Like the first example, the chance of the earthquake recurring within the next 50 years is 10%.

Figure 3: Parcel Sites in Memphis neighbourhood



(n=1274). Liquefaction hazard areas: Dark areas = high hazard, Light areas = low hazard.

Figure 4: *EP* curves for Building and Total Economic Value (*$Millions*) for Spatially Independent and Dependent Models (Blg_{SI} and Blg_{SD} are spatially independent and spatially dependent building-replacement costs, Tot_{SI} and Tot_{SD} are spatially independent and spatially dependent total economic value).

Using this figure, the appropriate exceedance probability corresponding to a risk level of $\rho = .005$ is obtained by dividing by .10 to yield:

$$EP = \rho / .10 = .005 / .10 = .05 \qquad (1)$$

The horizontal dashed line at $EP = .05$ in Figure 4 identifies the relevant *VaR* on each curve. Under spatial independence, the relevant value at risk lies in the interval between points ***a*** and ***c*** in Figure 4. Expected losses range from about $120M to $160M. It can be argued by opponents of this policy that the relevant *VaR* is most likely less than $150M, and that in view of the added undesirability of stricter code requirements on new development in this area, such a mitigation policy would not be worthwhile. However, in the presence of spatial dependencies, the relevant interval of values at risk is given by point ***b*** and point ***d***, which range from about $140M to $200M. When spatial dependencies are taken into account, the relevant value at risk is seen to be much larger, and could exceed $150M. Assuming spatial dependencies for valuation can lead to a higher estimate of potential damages. This factor alone could convince decision makers that the proposed mitigation policy is well worth the cost.

There are many additional costs resulting from amenity damage external to individual building sites. Including these amenities is part of the total value of the property. Although it is difficult to estimate the full extent of costs due to loss of amenities, their ultimate effect could depress local land values as well as building improvements. If so, then *Tot* may be taken as a reasonable value of losses at each site and have been used to construct the augmented *EP* curves, Tot_{SI} and Tot_{SD} in Figure 4.

4. DISCUSSION AND CONCLUSIONS

Analysis of a Memphis policy to implement an earthquake building standard and implied investment behaviour is a good example of the effect of uncertainty on a policy choice. We have used an example of earthquake triggered liquefaction to examine the impacts of scientific and socioeconomic uncertainty on a collective choice in a regional economic context. The benefits and costs of loss reduction measures are affected in several ways.

The two policy analyses show that there are situations when the regional economy would benefit from a mitigation regulation that is either paid for by individuals or with public subsidies, an ROI of at least 1.0. On the other hand, the examples included several plausible situations that demonstrate that government intervention would be inefficient, i.e., an ROI as small as 0.05. The uncertainty of the recurrence of the hazard has a substantial effect on the outcome of the analysis. In the first example, if the hazard occurs in the first year, the mitigation is certain to pay off. It is most likely that development will proceed at a reasonable pace over the time period. Depending on which mitigation cost estimate is used in the analysis, it can reveal individual risk aversion and regional risk preferences. When we use a 10% cost estimate, we accept the program more readily, an optimistic estimate of mitigation cost. In the second example, it is clear that including location amenities into the valuation increases the likelihood of program acceptance.

Now we return to the question of acceptable risk. To inform the decision maker we presented two examples of an application of mean loss / return risk approach that can be used to evaluate loss-reduction investment choices. Results of the comparison of different time periods, mitigation costs, estimates of asset value, and spatially correlated losses can substantively affect the choice of implementing a new policy. The investment decisions contain considerable uncertainty related to the benefits, costs, and effectiveness of a loss-reduction strategy. The planning horizon and spatial correlation are modelling assumptions that also affect the result. In case 1, the ROI for runs 2, 4, and 6 in Table 1 for the community suggests that sharing to pay for mitigation is beneficial to the community. The acceptable risk criterion requires a definition of a threshold for this criterion to be binding. If we were to apply this threshold as a maximum tolerable dollar limit of 10% of property valuation, $1B in example 1, only the unmitigated case of run 1 is unacceptable. All other runs would meet the criterion and the regulation should be implemented. Alternatively, if 5% of property valuation were the threshold, runs 4 and 6 would be acceptable. In case 2 accounting for spatial dependency or using total economic value for the analysis increases the probability of exceeding an acceptable risk threshold. Further, in case 2, when the *VaR* exceeds $150M for point ***c*** and point ***d*** in Figure 4, there are conditions when the potential benefits of the intervention are large.

Of course it is rarely the case that any single consideration will be decisive in such complex policy questions. The main point of the two examples is to show that the uncertainties associated with a policy choice and the possibility of spatial dependencies in earthquake outcomes constitute important factors that must be considered in the proper assessment of earthquake risks.

In summary, the benefits and costs of a building safety standard is a risky investment since the ROI to the community is unclear. Because the decision to implement the measure must be prior to experiencing an event, there are many uncertainties that arise when considering the policy. We have considered the problem as one of public choice. That is, the community decides whether the mitigation measure is adopted not the individual. We evaluated whether the risk of implementing a liquefaction resistant building code is acceptable to those who will pay for it. Second, uncertainty of input information to the evaluation affects the perceived outcome. The analysis should consider the decision risk associated with the uncertainty of the predicted damage state both temporally and spatially, and this risk makes decision making difficult.

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