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OPTIMIZING THE SELECTION OF REGIONAL EARTHQUAKE MITIGATION STRATEGIES

Atsuhiro DODO[1], Ningxiong XU[2], Rachel A. DAVIDSON[3], and Linda K. NOZICK[4]

SUMMARY

Even when a community recognizes its earthquake risk and wants to take action to mitigate future losses, funds available for such efforts are always limited. There is a need, therefore, for communities at risk to undertake systematic regional earthquake mitigation planning to decide: (1) how much to spend on pre-event mitigation that aims to reduce future losses versus waiting until after an event and paying for recovery, and (2) how to allocate the mitigation funds among the many possible mitigation activities so as to minimize overall risk. This paper describes the challenges and potential benefits of such regional mitigation planning analysis. Three alternative optimization model formulations are presented—two linear programs and one stochastic program. A small case study in Los Angeles illustrates the type of results they can provide.

INTRODUCTION

Regional earthquake mitigation planning involves: (1) determining how much to spend on pre-event mitigation that aims to reduce future losses versus waiting until after an event and paying for recovery, and (2) determining which of the many possible mitigation activities to fund so as to minimize overall risk. Since communities at risk always have limited budgets, they are always implicitly if not explicitly making choices among the various possible ways to manage risk. If they do not invest pre-event, by default they are planning to manage risk by spending on post-earthquake recovery. To the extent that a community can systematically compare the available management strategies, they are more likely to use their limited funds in an optimal way. Recognizing the value of regional mitigation planning, the Disaster Mitigation Act of 2000 now mandates that state and local governments conduct such mitigation analysis as a condition of receiving Hazard Mitigation Grant Program (HMGP) funds (FEMA [1], [2]).

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[1] Ph.D. Candidate, School of Civil and Environmental Engineering, Hollister Hall, Cornell University, Ithaca, NY 14853-3501

[2] Research Associate, School of Civil and Environmental Engineering, Hollister Hall, Cornell University, Ithaca, NY 14853-3501

[3] Assistant Professor, School of Civil and Environmental Engineering, Hollister Hall, Cornell University, Ithaca, NY 14853-3501

[4] Professor, School of Civil and Environmental Engineering, Hollister Hall, Cornell University, Ithaca, NY 14853-3501

Specifically, to be eligible for HMGP funds, each state and local government must submit a mitigation plan to FEMA describing how it is prioritizing mitigation actions so that its overall mitigation strategy is cost-effective and maximizes overall wealth.

Despite their potential usefulness, methods supporting regional mitigation planning are not well-developed. Currently available loss estimation models provide increasingly thorough and accurate estimates of regional risk, but offer limited guidance about how to use that information to make mitigation resource allocation decisions. For example, *HAZUS*, FEMA's standardized national loss estimation modeling software, estimates regional losses for earthquakes, wind, and flood; for all types of buildings and lifelines; including direct and indirect economic and social losses (FEMA [3]). For mitigation analysis, however, it can only be used with a trial-and-error approach to evaluate mitigation alternatives (FEMA [4]). Losses can be estimated with and without implementation of a particular mitigation alternative to evaluate the alternative's effectiveness. The relative costs of the alternatives, the budget, and the specific objectives are not incorporated, and only a small set of pre-defined mitigation alternatives can be considered. Previous work in resource allocation for natural disaster risk management has been of four main types: deterministic net present value (NPV) or benefit-cost analysis, stochastic NPV analysis, multiattribute utility models, and optimization models. Dodo *et al.* [5] (in review) summarizes the literature and identifies some gaps that remain. Almost all previous studies compare a small set of pre-defined alternatives and select the best one, rather than using an optimization approach to choose the best combination of alternatives subject to budget constraints. Most past studies have estimated benefits as those that would be realized if a particular earthquake scenario occurred, or if the annual expected ground shaking occurred. As discussed below, for spatially distributed risk management alternatives, this can lead to a suboptimal solution. In a related point, most work has compared alternatives based on the expected value of benefits, ignoring the large variability in benefits that results from the fact that different earthquakes may or may not occur. Finally, past research has typically neglected the dynamics of the resource allocation decisionmaking situation.

This paper introduces a set of possible optimization model formulations to support systematic regional earthquake mitigation analysis. They are designed to be integrated with an existing regional loss estimation model, such as *HAZUS*, which can be used to estimate losses avoided (benefits) of the possible mitigation alternatives. The next two sections discuss the benefits and challenges associated with regional earthquake mitigation analysis. The three possible optimization formulations are then presented, followed by sample results from an illustrative case study using one of the formulations. The paper concludes with summary remarks and suggestions for future work.

BENEFITS OF REGIONAL MITIGATION ANALYSIS

General resource allocation support

Optimization or some other systematic method for regional earthquake mitigation planning would be useful in providing a sound, replicable, transparent basis for earthquake risk reduction resource allocation decisions. It can guide the allocation of resources between pre-earthquake and post-earthquake efforts, and among various alternative pre-earthquake strategies. Possible pre-earthquake investments include, for example, structural upgrading, non-structural upgrading (e.g., bracing water heaters), public education, removing structures from hazardous areas, emergency planning, buying insurance, and saving money (i.e., self-insuring). Mitigation is a particular type of pre-earthquake endeavor that aims to reduce losses (as opposed to spreading them across time or groups of people). Post-earthquake expenditures are simply payments required to repair damage and enable recovery after an earthquake occurs. Some pre-earthquake investment is desirable, because especially when business interruption and indirect losses are considered, avoiding damage is generally less expensive than repairing it. In addition, mitigation can help minimize human losses, whereas post-earthquake spending cannot. Nevertheless, if no earthquake occurs in a reasonable time horizon, the pre-earthquake investment may have been wasted, in the sense that the benefits are never realized (although there may be psychological benefits to feeling safer). Even if an earthquake occurs, if it happens in the distant future, the discounting effect may render pre-earthquake investment less desirable than post-earthquake spending. Therefore, neither unlimited investment nor zero investment in pre-earthquake investments are likely to be optimal. A method to determine the optimal balance between the two could provide importance guidance.

It is also not at all obvious how to allocate a given pre-earthquake investment budget among the myriad possible mitigation alternatives in an optimal way. Mitigation alternatives differ in cost; who pays the cost; the magnitude, variability, and type of the benefits; and who receives them. For example, providing limited upgrading to many structures may reduce the likelihood of a large loss to any one, but may not protect against small losses. Upgrading a few structures completely may eliminate losses if the earthquake occurs right near those structures, but may have no positive effect if the earthquake occurs elsewhere.

Uncertainty in the estimation of both costs and benefits is unavoidable. By allowing examination of the sensitivity of its recommendations to those uncertainties, however, an optimization model could provide the user insight as to how robust the recommendations are, to ensure that they are used in a manner commensurable with the level of precision the available data afford. The user could use the model to explore the relative effects of the many inputs to the decisions (e.g., timing of earthquakes, risk attitudes).

Specific examples of use

Optimization models could also help local and state risk managers comply with a few specific, federally-mandated tasks. The Disaster Mitigation Act of 2000 states that, to be eligible for HMGP funds, each state and local government must submit a mitigation plan to FEMA describing how it is prioritizing mitigation actions so that its overall mitigation strategy is cost-effective and maximizes overall wealth (FEMA [1]). The models could help states and local governments prepare those required mitigation plans. After an earthquake, many applications for HMGP grants are submitted, and need to be evaluated quickly and rationally. By systematically comparing regional strategies (e.g., upgrade all unreinforced masonry buildings in a census tract), the proposed methodology can help streamline administration of the HMGP by providing a mechanism for "block grant" approval, just as the RAMP program did after the 1994 Northridge earthquake (Seligson *et al.* [6]). The Small Business Administration's Pre-Disaster Mitigation Loan Program makes low-interest, fixed-rate loans to small businesses so they can implement mitigation measures. To be eligible, the business must "conform to the priorities and goals of the mitigation plan for the community, as defined by FEMA, in which the business is located" (U.S. SBA [7]). Optimization models like those described below could help the local or state mitigation official decide which applications to approve.

CHALLENGES OF REGIONAL MITIGATION ANALYSIS

Resource allocation for regional earthquake risk management is a challenging problem for many reasons. It is characterized by having: (1) multiple objectives, (2) numerous alternatives, and (3) difficult benefit calculation; and by being (4) dynamic, (5) calculative intensive, and (6) data intensive. There are many objectives that might be considered based on the various types of loss and different risk attitudes. A community's objectives may include, for example, minimizing the overall expected net present value of its investments or minimizing the probability of an extreme loss. It might involve a tradeoff between minimizing economic and life loss. There are also numerous alternative risk management strategies that might be considered. The main types include structural, non-structural, land use, financial, and education risk reduction efforts. Within each type, there are many specific alternatives. For example, considering only structural upgrading strategies, one could consider targeting different groups of buildings, areas, or people, and one could consider different methods and degrees of upgrading.

Any comparison of possible risk management efforts has to include estimation of the benefits and costs associated with each alternative effort. Estimating the benefits of regional risk is difficult for a few reasons. The benefits of investment are considered to be the losses avoided by undertaking the investment, and therefore, losses have to be calculated for some specified earthquake occurrence. Ideally, all possible earthquakes with their associated probabilities of occurrence would be considered. Almost all past studies, however, have calculated benefits either assuming a single (or a few) specified earthquake(s) occurs (e.g., Sarin [8], Seligson *et al.* [6], Shah *et al.* [9]), or assuming that the ground shaking with a specified annual probability of exceedence occurs (e.g., FEMA [10], [11]; Altay *et al.* [12]). Basing the benefit estimates on one, or even a few, scenarios is not adequate, because what is an optimal investment strategy for one earthquake is not necessarily optimal for all earthquakes, and in fact can be completely ineffective for other earthquakes. Using the annual expected ground shaking is better because it considers all possible earthquakes, but it does not account for the spatial correlation among losses, and therefore mitigation benefits associated with spatially distributed alternatives. One approach used by Chang *et al.* [13] and Campbell and Seligson [14] is to select a finite set of earthquakes that can represent the regional seismicity and still be few enough to be amenable to resource allocation analysis. They then estimate a "hazard consistent" annual probability for each earthquake scenario that represents the likelihood that earthquakes of that type occur. The process of selecting an appropriate set of earthquake scenarios and determining appropriate "hazard consistent" probabilities of occurrence is difficult, however. Estimating benefits is also difficult because it requires estimating regional losses with and without implementation of each potential risk reduction alternative. This can be done using a regional loss estimation model, such as *HAZUS*, but each of those calculations are in themselves somewhat data- and calculation-intensive. Furthermore, the process of representing implementation of a risk reduction alternative in a loss estimation model is not simple. It is typically done by adjusting the appropriate input parameters. For example, to represent implementation of a structural upgrading strategy, the fragility curves of the affected structures would be adjusted. Determining what exactly to adjust and by how much is a challenging task.

With the exception of Shah *et al.* [9], past studies have not considered decision timing, assuming instead that all investments are made at the present time. Dynamic investment scheduling is preferable because risk managers make investments periodically, and the return on the investments will depend on when during the time horizon earthquakes occur (if they do). Incorporating the dynamics into the analysis complicates the modeling as well.

Resource allocation for regional earthquake risk management is also difficult because the multiple objectives, numerous alternatives, and difficult benefit calculations mean that it is typically a calculation-intensive problem. Depending on the scope of the analysis and how the model is formulated, the number of variables included can get large enough to require special solution algorithms. Finally, like the straightforward loss estimation analyses on which they rely, resource allocation models require a large amount of data that is often difficult to obtain, such as, data describing the magnitude and character of the regional earthquake hazard, building inventory and its vulnerability, costs associated with all possible alternatives, available budget, and specific regional objectives for risk management. The models presented in this paper aim to address some of these challenges.

ALTERNATIVE OPTIMIZATION MODEL FORMULATIONS

Since the objectives and alternatives considered will vary depending on the specific user and intended use, there are many possible optimization model formulations that might be appropriate for different situations. For example, a local risk manager seeking support in administering the Small Business Administration's Pre-Disaster Mitigation Loan Program might need a formulation that focuses on allocating a fixed budget so as to minimize expected economic loss through risk reduction strategies implemented in small businesses. A state risk manager may require support in deciding what the total state budget should be for pre-event mitigation spending versus post-event recovery spending. In some cases, different uses can be accommodated by just changing variable values within a single formulation; in some cases, they require new formulations and/or new solution algorithms. In this section, three alternative formulations are described briefly.

Scope of model formulations

In all three model formulations, the mitigation alternatives considered are structural upgrading policies for groups of buildings. Buildings are grouped into categories based on their census tract locations, structural types (e.g., mid-rise steel braced frame, low-rise concrete shear wall), occupancy types (e.g., single-family dwelling, hospital), and design levels (i.e., built to a low, moderate, or high seismic code). One mitigation alternative considered is to upgrade some square footage of buildings of a particular structural and occupancy type in a census tract from one design level to another. The set of mitigation alternatives considered is created by all possible combinations of structural, occupancy types, census tracts, and design levels. The model assumes that a finite set of earthquake scenarios with associated probabilities can be identified to represent the region's seismicity, as in Chang *et al.* [13]. Except mitigation costs, all input for the model can be obtained from any regional loss estimation model, such as *HAZUS*.

The models are formulated to represent the evolving condition of a region's building inventory. In each time period, decisions are made about which buildings to mitigate and to what design level, those upgrades are implemented, and then either one of the possible earthquakes occurs or none does with assigned probabilities. For each possible seismic event, the expected damage condition of the building inventory is calculated, and assuming all damage is repaired, the post-earthquake recovery cost is estimated. It is assumed that after an earthquake, each building enters one of a small set of damage states (e.g., no damage, slight damage, moderate damage). The probability that a building of a given type enters each of the damage states after an earthquake is assumed to be a function of the ground shaking at the site and the vulnerability of that type. It can be calculated by a regional loss estimation model.

Formulation 1. Allocating a specified pre-earthquake budget

In the first formulation, which is the simplest of the three, it is assumed that the budget for pre-event spending is set, and thus the model considers only the question of how to allocate that specified budget among mitigation alternatives, not the question of what the budget should be for pre-earthquake spending (versus for post-earthquake recovery). This first model is a linear program in which the objective is to minimize the expected post-earthquake recovery cost:

$$\min \sum_{t} \sum_{i} \sum_{j} \sum_{k} \sum_{c} \sum_{d} \sum_{c'} R_{ijkt}^{dcc'} \, y_{ijkt}^{dcc'} \tag{1}$$

where $R_{ijkt}^{dcc'}$ is the per square foot recovery cost for buildings during time period t in census tract k that are of structural type i and occupancy type j which were designed to seismic code c and have entered damage state d to be repaired to condition c', and $y_{ijkt}^{dcc'}$ are the decision variables, the square footage in census tract k, of structural type i and occupancy type j that was in condition c prior to the earthquake and has entered damage state d as a result of the earthquake and is to be repaired to seismic code c' during time period t. The recovery cost includes the cost to repair damaged buildings to their pre-earthquake condition c, plus any additional cost incurred if the building is upgraded at that time to condition $c' > c$. Assuming all damage is repaired, the repair cost is equivalent to what *HAZUS* would call loss.

The formulation includes constraints to ensure conservation of square footage from time step to time step. For example, one constraint ensures that the square footage in each building class (defined by *i*, *j*, *k*) in each time period designed to each seismic code equals the square footage that has been upgraded to that seismic code during the previous time step, or was already at that code level and was not upgraded. There are nonnegativity constraints on the decision variables, and there is an annual budget constraint to ensure that no more or less than the allocated pre-event annual budget is spent on mitigation. The results of this first formulation indicate how to allocate the mitigation budget among mitigation alternatives, and what the expected total post-earthquake recovery costs will be.

Because repair and mitigation decisions are by census tract, building type, time step, seismic code design level, and damage state, the number of variables in this model can get extremely large for an application on the order of the size of California. If the scope of the problem is limited, for example by limiting the number of census tracts or building types considered, then it is possible to solve the model using a commercial linear programming solver. For large problems, however, a special solution technique will be required. The formulation is highly structured so a special solution procedure is very likely to be possible.

Formulation 2. Minimizing expected value of total cost

In the second formulation, the problem is expanded to address the question of what the budget for pre-event mitigation spending should be (versus post-event recovery), as well as the question of how to allocate that mitigation budget among alternative mitigation efforts. The model is still a linear program with the same decision variables, but the objective is now to minimize the present value of the total mitigation and expected post-earthquake recovery cost. The budget constraint is relaxed so that in this model no more than a maximum annual budget can be spent on mitigation, but the entire sum does not have to be spent if saving it for post-earthquake recovery is a better alternative. As with the first formulation, this model can be solved either by a standard linear program solver if the problem is not too big, or by a special method if it is.

Formulation 3. Minimizing risk of a large loss

Both of the first two model formulations make decisions based on the annual expected value of post-earthquake recovery costs. In reality, future benefits of mitigation (i.e., reduction in recovery costs) are actually stochastic, and a decisionmaker may be interested not only in the expected benefit, but in the variability of benefits as well. Because earthquakes are low probability-high consequence events, the probability distribution of net present value for earthquake investments has a large variance (i.e., no benefit if no earthquake occurs to significant benefits if a large one does). Therefore, risk managers probably do not want to make decisions based solely on expected values. They may also want to minimize the probability of a large loss, for example. To account for the whole probability density function of benefits associated with a mitigation alternative, not just the expected value, the third formulation uses a stochastic programming formulation to trade-off expected net present value against the probability of large losses.

CASE STUDY RESULTS

Case study scope

This section presents a case study using the first model formulation described above. It is intended to illustrate the type of results that a regional earthquake mitigation analysis optimization model can provide. The case study was done for one occupancy type (government buildings) in a 10-census-tract portion of Los Angeles County, CA (Figure 1). Within that occupancy type and area, there are 7 structural types represented (Table 1). Across these 10 census tracts, there are about 86,300 sq. ft. of government building space, of which about 20%, 50%, and 30% are designed to low, moderate, and high seismic code, respectively. It was assumed that $25,000 is available for mitigation in each of the first five years, the valuation period is 30 years, the time step is one year, and the annual interest rate is 5%. About 125,000 variables were required for this illustrative example.

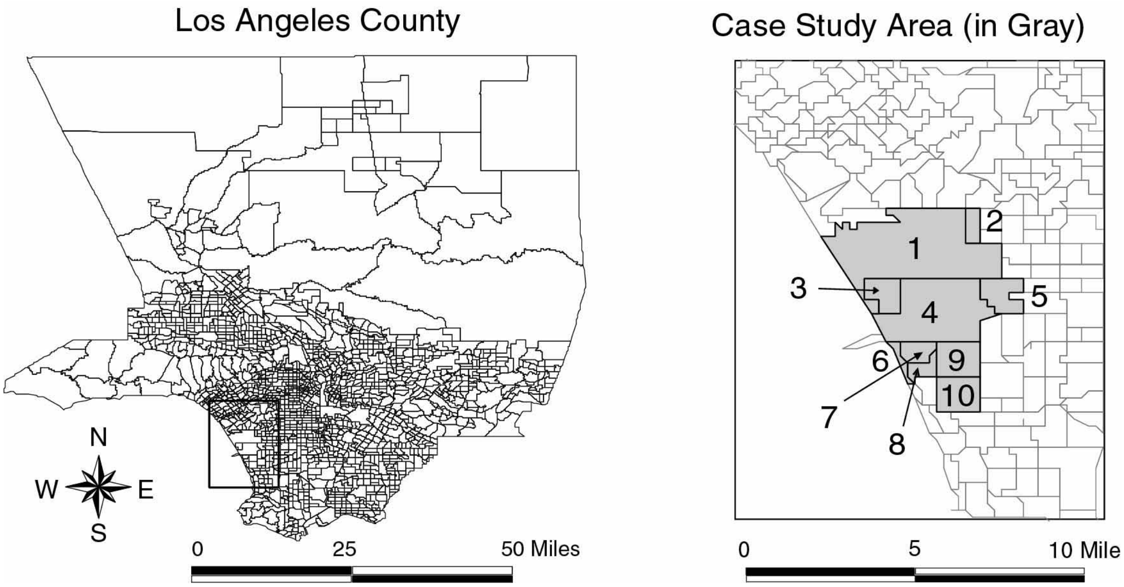

Figure 1. Case study census tracts in Los Angeles County

Table 1. Structural types in proof of concept case study

***HAZUS* type**	**Description**	**Area (sq. ft.)**
W2	Wood, commercial and industrial	8,320
S1L	Steel moment frame (low rise)	15,600
S2L	Steel braced frame (low rise)	4,160
S4L	Steel frame with cast-in-place concrete shear walls (low-rise)	7,280
C2L	Concrete shear walls (low-rise)	33,280
PC2L	Precast concrete frames with concrete shear walls (low-rise)	4,160
RM1L	Reinforced masonry bearing walls with wood or metal deck diaphragms (low-rise)	13,520
	Total	86,320

The analysis assumes that just 47 earthquakes are possible, each with an associated annual "hazard-consistent" probability of occurrence, so that together they approximate the regional seismicity. The 47 earthquakes are those identified by Chang *et al.* [13] for a risk analysis of the highway network in Los Angeles and Orange Counties. The case study analysis uses *HAZUS* default data, and considers only structural, non-structural, inventory, contents, and time losses in the estimation of recovery costs, not for example, indirect economic or human life losses. It assumes the same 3 possible seismic design levels (designed to low, moderate, and high seismic code), and the same 5 possible damage states (no, slight, moderate, extensive, and complete damage) as in *HAZUS*.

Case study results

The case study results can be used to answer many questions, including: (1) Given the recommended mitigation spending strategy, what are the expected post-earthquake recovery costs over time?; (2) Given a set amount of annual mitigation expenditures, which buildings should be mitigated and which are expected to require recovery expenditures, by structural type and by census tract?; and (3) How effective will the recommended strategy be if it turns out that one particular earthquake happens. These questions are examined in turn for the case study analysis.

The solution recommends spending the budget exclusively on upgrading the low seismic code buildings to high seismic code (as opposed to upgrading moderate seismic code buildings). About 1,620 sq. ft, or 10% of the low seismic code floor area is upgraded in each of the 5 years, so that after all upgrading is complete, 40% of the low code area has been upgraded to the high seismic code design level. The expected annual post-earthquake recovery cost is reduced from $27,000 in Year 1 to $23,200 after Year 5, the last year in which mitigation is done (Figure 2). Still, the present value of expected post-earthquake recovery costs over the 30 years ($384,000) is more than three times the present value of mitigation costs over the 30 years ($114,000). Without discounting, recovery costs are 5.6 times as large as mitigation costs, since the mitigation costs occur early in the valuation period. For specific structural types, that ratio varies from 2 to 15.

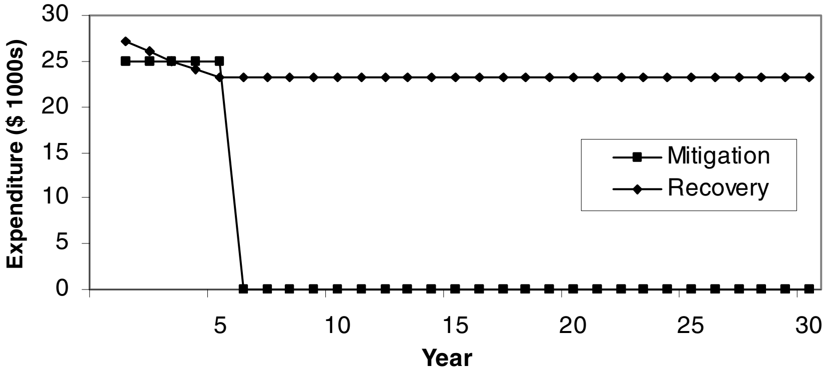

Figure 2. Mitigation and recovery expenditures over time based on solution

Figure 3 shows the total and per square foot amounts that, according to the optimization solution, should be spent on mitigation, by structural type. It indicates that the largest per square foot mitigation expenditures should be on precast concrete frames, PC2L, ($3.9/sq. ft.), steel moment frames, S1L, ($2.3/sq. ft.), and steel frame with concrete shear walls, S4L, ($2.2/sq. ft.). All of the low code floor area of PC2L and S4L and 84% of the S1L low code floor area should be mitigated. This makes sense, since these structural types have the largest annual probability of at least moderate damage when they are designed to low seismic code. Commercial wood (W2), on the other hand, has by far the lowest annual probability of damage, and therefore, ends up having none of its area mitigated. The total amount of mitigation spending on a structural type depends on both the per square foot spending and the amount of low code area available to be mitigated. The structural types with the most low code area are concrete shear walls (C2L), steel moment frames (S1L), and reinforced masonry (RM1L), which have 42%, 16%, and 16% of the low code area in the 10 census tracts, respectively. Since steel moment frames, S1L, is the only structural type with relatively high per square foot mitigation expenditures and large amount of low code area to be mitigated, the solution recommends spending more mitigation funds on S1L than any other structural type, $36,000.

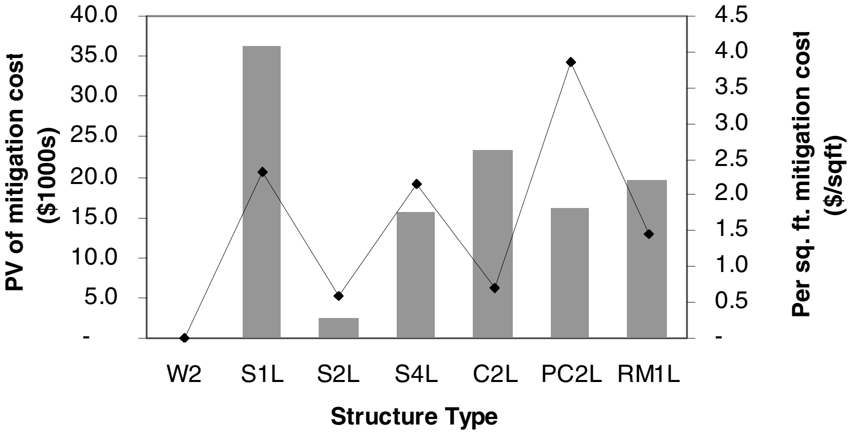

Figure 3. Total and per square foot mitigation expenditures by structural type (column is total; line is per square foot)

Figure 4 shows the total and per square foot expected post-earthquake recovery costs, by structural type. Recovery funds will be spent mostly on concrete shear wall buildings, C2L ($166,000). Note that since 100% of the low code area of S4L and PC2L were mitigated, they have relatively low expected recovery costs, $26,000 and $19,000, respectively. Since W2 has low annual probability of damage, it also has a low expected recovery cost, $23,000.

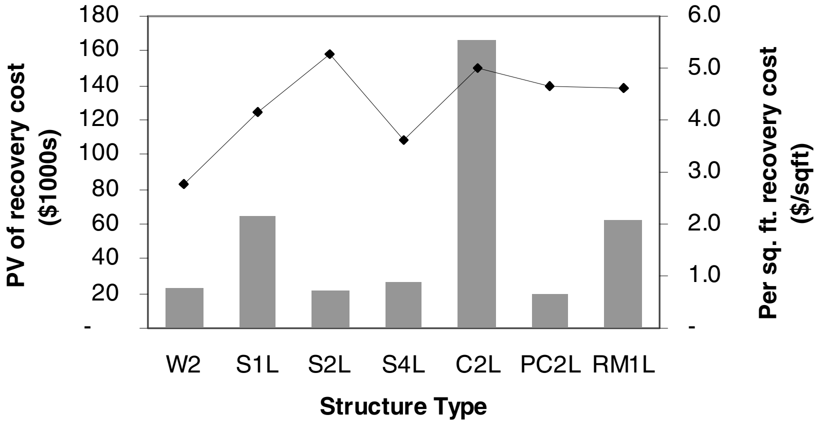

Figure 4. Total and per square foot expected recovery expenditures by structural type (column is total; line is per square foot)

Figure 5 shows the total and per square foot amounts that the optimization solution indicates should be spent on mitigation, by census tract. The largest per square foot mitigation expenditures are for Tracts 1, 10, and 2 ($2.9, $2.8, and $2.6 per square foot, respectively). The solution recommends upgrading 89% of the low code area in Tracts 1 and 10, and 84% in Tract 2. These tracts are also those that have the largest annual probability of being in at least moderate damage state. However, since the 10 tracts are all less than 10 miles apart and the distribution of structural types is relatively constant across tracts, the annual expected ground shaking and expected damage does not vary too much among them. Although three tracts have large per square foot mitigation expenditure, Tract 10 ends up with a total expenditure that is 50% greater than the next highest expenditure because it is the only one of the three that also has a lot of low code floor area (16% of all the low code area in the 10 tracts, the most of any tract).

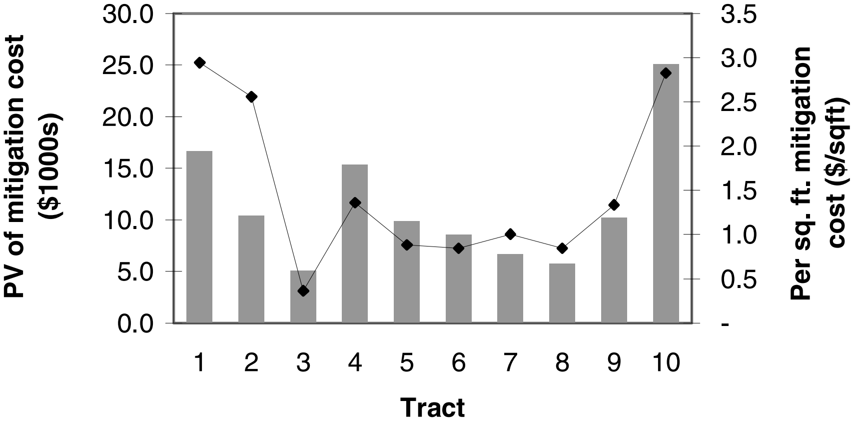

Figure 5. Total and per square foot mitigation expenditures by census tract (column is total; line is per square foot)

The per square foot expected post-earthquake recovery costs are fairly constant across census tracts, again probably because the tracts are in close proximity and the annual expected damage does not vary greatly between them (Figure 6). The largest total expected recovery costs are in those tracts with the greatest amount of low code floor area, Tracts 3, 5, 4, and 6. Note also that since most of the low code area was mitigated in Tracts 1, 10, and 2, those tracts have relatively low post-earthquake recovery costs.

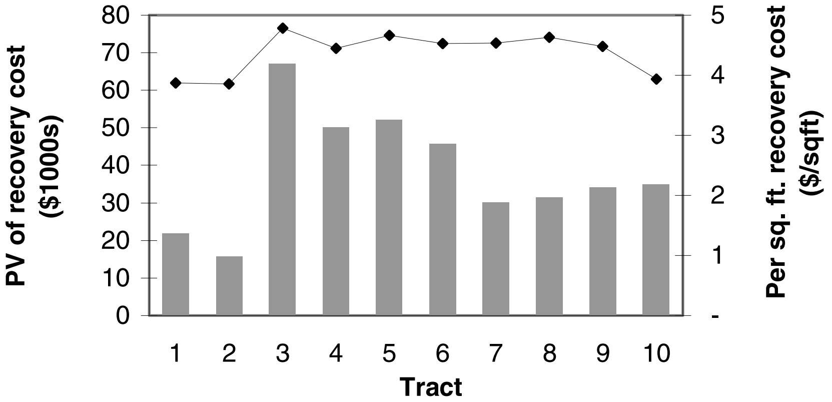

Figure 6. Total and per square foot expected recovery expenditures by census tract (column is total; line is per square foot)

Figure 7 presents the total benefit of mitigation (loss without mitigation less loss with mitigation as recommended by the optimization) for each of the 47 earthquake scenarios. It shows that the benefits can differ greatly depending on which earthquake occurs. The recommended mitigation strategy will provide no benefit if Earthquake Scenario A occurs, which is relatively likely. It will provide $418,000 of benefit if the less likely Earthquake Scenario B occurs. In general, the earthquake scenarios that have larger magnitudes and are closer to the census tracts of interest result in great benefits.

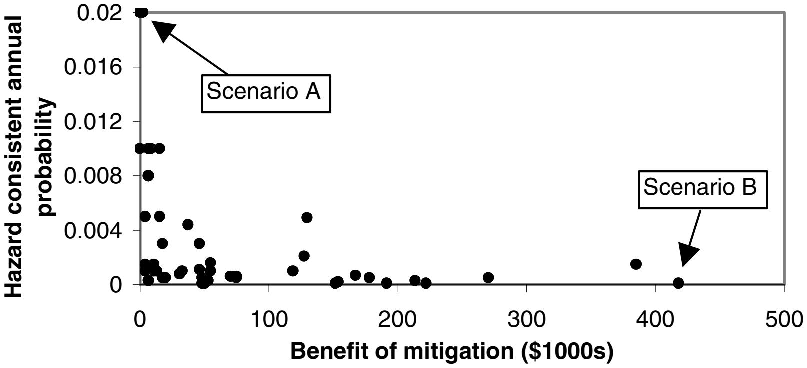

Figure 7. Mitigation benefit for each earthquake scenario

The output shown in Figures 2 to 7 is illustrative of the type that the three optimization model formulations can produce. It could be helpful in supporting various strategic community earthquake mitigation planning decisions.

CONCLUSIONS AND FUTURE WORK

This paper has introduced the challenge of regional earthquake mitigation analysis—supporting community decisions about (1) how much to spend on pre-event mitigation that aims to reduce future losses versus waiting until after an event and paying for recovery, and (2) which of the many possible mitigation activities to fund so as to minimize overall risk. Three optimization model formulations are proposed to address this problem, and illustrative results are presented for a small case study to demonstrate the type of solutions such formulations could provide.

This paper discusses a first step in this area of research. Much works remains to develop alternative formulations that can, for example, address other objectives and alternatives, and to develop solution algorithms that can solve those formulations for realistic problems. Significant improvements are also necessary in the collection of the input data required for these types of resource allocation decision support models, in particular, data on the costs of various mitigation alternatives.

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