Using Cost-Benefit Analysis to Evaluate Mitigation for Lifeline Systems

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Research Objectives

The purpose of this research is to examine how cost-benefit analysis (CBA) can be utilized to evaluate the attractiveness of mitigation for lifeline systems subject to earthquake ground motion. We propose a framework for the CBA that can be used in conjunction with work being completed by other researchers at MCEER (Shinozuka et al., 2000; Chang et al., 2000). With their development of fragility curves and insight into specific utility lifelines systems, our framework is useful for the next step in the analysis. In this paper, we use an example of a transportation system to show the CBA framework. Then, we consider two case studies to show the effects of the disruption of utility lifeline service on two stakeholders in the analysis. First, the indirect economic loss to business owners is studied, and then, the cost to public agencies to shelter displaced residents is considered.

The two lifelines serving as case studies for this work are the electric power system in Shelby County, Tennessee [building on previous work done at MCEER] and the water distribution system in Alameda and Contra Costa Counties, California [working with the East Bay Municipal Utility District (EBMUD)]. Our research provides a framework to link data from the physical and engineering sciences (i.e., seismology of the region and vulnerability of the lifeline) with the social sciences (i.e., costs of natural disasters and public policy implications of mitigation).

Cost-benefit analysis (CBA) is a systematic procedure for evaluating decisions that have an impact on society. There are different ways to conduct a valid CBA, depending on the information one has and the nature of the problem at hand. We chose a simplified five-step procedure to illustrate this approach (Figure 1). A more comprehensive approach, which incorporates several additional steps, is discussed in Boardman et al. (2001). The five-step procedure includes: defining the nature of the problem, including the alternative options and interested parties; determining the direct cost of the mitigation alternatives; determining the benefits of mitigation, via the difference between the loss to the system with and without mitigation; calculating the attractiveness of the mitigation alternatives; and, finally, choosing the best alternative.

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- *Water distribution systems in Alameda and Contra Costa Counties, California (working with East Bay Municipal Utility District)*

These steps were chosen keeping in mind the complex process of estimating losses to lifeline systems and evaluating the benefits of mitigation to the system. Previous work performed at the Wharton School analyzed the cost-effectiveness of mitigation to residential structures (Kleindorfer and Kunreuther, 1999). In this analysis, the reduction in damage to the structure was accomplished through a shift in the fragility (i.e., vulnerability) curve in the analysis and a recalculation of the expected loss. If the expected reduction in loss exceeds the cost of undertaking mitigation (e.g., step 4 in Figure 1), then one can justify investing in it.

The analysis of the benefits of mitigating lifeline systems is a more complicated process than for a residential structure. Lifeline systems have unique characteristics, which make the calculation of damage to the system difficult (Chung et al., 1995). First, the loss of function of the lifeline is dependent on many parts of the system, often buried underground, spread across a large geographic region rather than at one location (e.g., as in the case of a residential structure). For example, in analyzing the functional

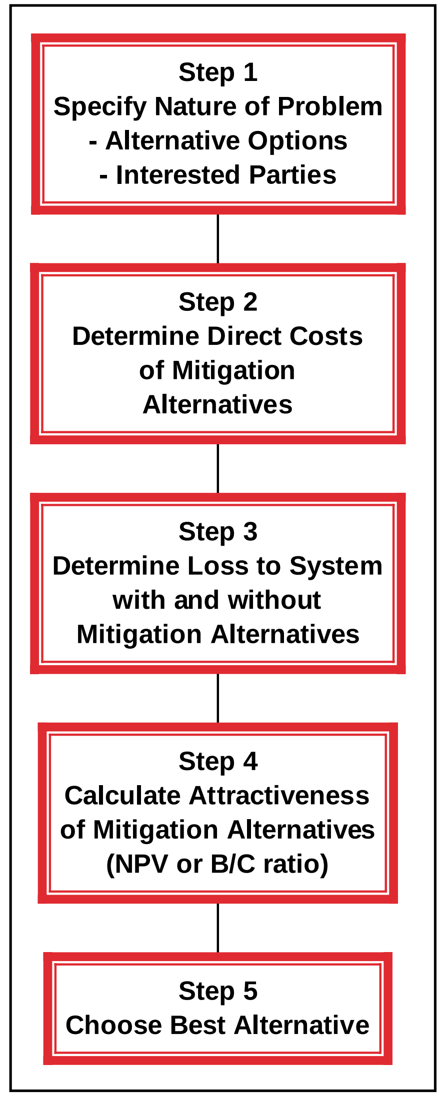


Figure 1. Simplified Cost-Benefit Analysis for Lifeline Systems

The cost to mitigate is primarily undertaken by owners, but everyone in a region benefits from uninterrupted or faster restoration of lifeline service after a disaster. Therefore, the primary users of this research are the operators of lifeline systems, which could be government agencies or private sector organizations who fund the cost of implementing mitigation measures. Cost benefit analyses can help determine if the expected reduction in loss exceeds the cost of undertaking mitigation. The thrust of the research is to encourage and justify implementation of retrofit schemes for a variety of lifeline systems.

reliability of an electric power transmission network, one needs to consider the loss of connectivity of different substations, as well as the vulnerability of the various components of each substation, to the system as a whole. This process can be even more complex when one must consider the collocation of different lifeline systems. For example, if the electric power system's cables are adjacent to the water distribution system's pipelines underground, damage to one can compound the damage to the other.

Second, the damage to the system, measured in outage or service disruption, needs to be translated into dollar loss to the interested parties in the cost-benefit analysis. The benefits of mitigation are the difference between the loss without mitigation and the loss with mitigation. The costs of mitigating the system must also be estimated. While these mitigation costs are generally borne by the owner and operator of the lifeline, everyone in the region benefits from the uninterrupted or faster restoration lifeline service after a disaster.[1] Therefore, the attractiveness of mitigation to a lifeline system should be viewed as beneficial to society as a whole, calculated via a societal benefit-cost ratio. The thrust of this research is to encourage and justify funding for earthquake hazard mitigation of lifeline systems.

The Five-Step Procedure

Step 1: Specify Nature of the Problem

To initiate a CBA, one needs to specify the options that are being considered and the interested parties in the process. Normally, one alternative is the status quo. In the case of the current analyses, the status quo refers to the current vulnerability of the lifeline system without a mitigation measure in place. The status quo is likely to be the reference point for evaluating how well other alternatives perform. In general, if there is sufficient political dissatisfaction with the proposed mitigation options and/or the perceived expected benefits (i.e., reduction in lifeline disruption) are considered to be less than the expected costs to mitigate the system, then the status quo will be maintained.

For the utility lifeline problem we are studying in Shelby County, Tennessee, the status quo is the vulnerability of the electric power system currently in place. An alternative option is to retrofit or replace some or all of the substation equipment components in the electric power system so they are still functional after a severe earthquake. For example, the transformers in the substations can be seismically retrofitted to withstand lateral loading. Alternatively, the high-voltage transformer bushings can be replaced before an earthquake occurs.

Each of the alternative options will impact a number of individuals, groups and organizations in our society. It is important to indicate who will benefit and who will pay the costs associated with different alternative options when undertaking a CBA analysis. In the case of a lifeline system, one needs to consider a broad set of interested parties. These include residents and business owners affected by the earthquake, public sector agencies that must respond and fund the re-

Links to Current Research

Program 1: Seismic Evaluation and Retrofit of Lifeline Networks

- *Task 1.3 Loss Estimation Methodologies*
- *Task 1.4 Memphis Lifeline Systems Analysis*
- *Task 1.10 Rehabilitation Strategies for Lifelines*

Program 2: Seismic Retrofit of Hospitals

"The attractiveness of mitigation to a lifeline system should be viewed as beneficial to society as a whole."

covery process, as well as the general taxpayer that will bear some of the repair costs of the damaged lifeline system(s).

Step 2: Determine Direct Costs of Mitigation Alternatives

For each mitigation alternative (i.e., all alternatives except the status quo), one needs to specify the direct cost to implement the mitigation measure. For a lifeline system, the owner and operator of the system incurs the costs of mitigation. In a large majority of the cases in the United States, it is a public sector agency. Furthermore, the costs are most likely direct monetary costs to structurally retrofit or replace some components of the lifeline system. In the case studies we will present, a government agency incurs the direct cost of mitigation.

Step 3: Determine the Benefits of Mitigation Alternatives

Once the costs are estimated for each mitigation alternative, one needs to specify the potential benefits that impact each of the interested parties. In the case of seismic risk, one considers either a scenario earthquake event or a set of scenario earthquakes of different magnitudes, location, duration, and attenuation that can affect the system. With the specification of the vulnerability of the lifeline system, the damage to the various components of the system is then estimated for each alternative option. Then, overall system reliability is estimated.

With the status quo, there will be no benefits because no retrofit or replacement scheme is characterized. In other words, the status quo is the damage to the system without mitigation. In the other alternatives, benefits will be estimated from the change in damage to the system with the status quo and damage to the system with mitigation in place. Once the system reliability with each mitigation alternative has been specified, it should be possible to quantify the effects of serviceability to the interested parties by attaching a dollar value to them. The calculation from damage to loss is a complicated process and will differ from one interested party to another (e.g., losses to industry from business interruption differs from residential loss due to relocation).

Step 4: Calculate Attractiveness of Mitigation Alternatives

In order to calculate the attractiveness of mitigation, the nature of the benefits to each of the interested parties is estimated and compared to the upfront costs of mitigation. With respect to lifelines, the alternatives involve a degree of outage or serviceability over a prescribed time horizon (T). One characterizes the impact on the key interested parties during the days or weeks that the system will not be fully functional. One then utilizes a societal discount rate to convert the benefits and costs of the alternative over time into a net present value (NPV). If the NPV is greater than zero, then the alternative is considered attractive. Alternatively, one could calculate the ratio of the discounted benefits to the upfront costs to determine the attractiveness of the alternative. Whenever this ratio exceeds 1 the alternative is viewed as desirable.

To illustrate, consider the case of damage to a water distribution system from a scenario earthquake event. There could be a period of time where businesses may not be able to operate in a normal manner due to loss of service. If mitigation were implemented (e.g., underground pipelines were replaced or retrofitted), the time to restore water to businesses may be shortened. Suppose that the mitigation measure reduced the restoration time by 3 days following a severe earthquake. The resulting savings in business interruption costs during this three-day time interval following the earthquake are then discounted back to the present. These savings are multiplied by the annual probability of such an earthquake occurring to compute the expected benefits of mitigation. A similar calculation would be made for any earthquake that could occur in the area. These savings are then summed up to determine the total expected benefits which are then compared to the upfront costs of mitigation to determine the cost-effectiveness of the mitigation measure.

One must be careful, however, when considering the time that service is unavailable to the users of certain lifeline systems. Depending on the type of system (e.g., transportation, water distribution, electric power), days without service are, on average, less with electric power systems than other types of systems. This is primarily due to the redundancy in these systems and the critical nature of electric power systems in emergency response and coordination following an earthquake (Chung et al., 1995).

Step 5: Choose the Best Alternative

Finally, once the attractiveness of each alternative is calculated through a net present value calculation or a ratio of the benefits to the costs, one can choose the alternative with the highest NPV or benefit-cost ratio. This criterion is based on the principle of allocating resources to its best possible use so that one behaves in an economically efficient manner.

Applying the Five-Step Procedure to a Transportation System

We now illustrate how the above five-step procedure of CBA can be utilized to evaluate mitigation for a lifeline system through a simple example. In the next section, we will indicate the types of data that are required to undertake different levels of analyses of more realistic problems.

Step 1: Specify Nature of the Problem

The following question has been posed to a public agency that owns and operates a transportation network in an earthquake prone region in the United States: Should the transportation agency seismically upgrade their 2,200 highway bridges so that they perform adequately in a major earthquake?

There are only two alternatives for this problem:

A1. Seismically retrofit the bridges
A2. Do not retrofit the bridges (i.e., maintain status quo)

There are a number of interested parties who are affected by this problem. These include the residents who use the bridges to commute to work, the businesses that use the transportation network to move goods, the owner of the transportation network, police and fire teams that cannot move across the bridge, environmental groups concerned with the impact of a col-

"Developing a meaningful cost-benefit analysis methodology requires bringing scientists, engineers and social scientists together to analyze a problem."

lapsed bridge on residents of the sea. We will focus on just the owner of the network to keep the analysis simple.

Step 2: Determine Direct Costs of Mitigation Alternatives

The direct cost associated with seismically retrofitting the bridges is the material and labor cost to complete the retrofit scheme. In this case, we assume that, on average (i.e., over 2,200 bridges), this cost is approximately $30 per square foot.

Step 3: Determine the Benefits of Mitigation Alternatives

The benefits of retrofitting the bridges depend on whether or not an earthquake occurs and the length of time (*T*) that the bridges are impaired after the earthquake with and without the retrofit scheme in place. For simplicity, we consider only one scenario event, with two possible outcomes: (1) the earthquake occurs with probability, *p*, or (2) no earthquake occurs with probability, *1-p*.

For this event, the benefits consist of several different impact categories. We will consider one category for this analysis: the damage to the bridges. Damage and loss will be the same or lower if the bridges are retrofitted (A1) than if they are not (A2). In other words, the benefits from mitigation are the reduction in costs to repair the damaged bridges. In this case, we assume that the cost to repair the damaged bridges without a retrofit scheme (i.e., replace the bridges) is $140 per square foot. With the retrofit scheme, the cost is zero.

Step 4: Calculate Attractiveness of Mitigation Alternatives

To determine the impact of retrofitting the bridges through a net present value calculation, three additional pieces of data are required: (1) the probability of the scenario earthquake, *p*; (2) the life of the bridge, *T*, in years; and (3) the annual societal discount rate, *d*.

As each of these parameters is varied, one will obtain a different relationship between the net present value (NPV) of the expected benefits and costs of A1 and A2. To illustrate this point, suppose that one utilized the following parameters to determine whether or not retrofitting the bridges is beneficial to the transportation department. First, the probability of the earthquake occurring, *p*, is a 1 in a 100-year event (i.e., *p* = 0.01). The life of the bridge, *T*, is 50 years, and the discount rate, *d*, is 4%.

Suppose an earthquake occurred and the bridges were retrofitted. Then, the reduction in losses from this retrofit scheme is $140 per square foot, and the expected benefits from mitigation would be calculated (1/100)(140) = 1.4. With *d* = 4%, the expected discounted benefits of retrofitting over the 50 year life of the average bridge would be $30 per square foot. As we vary each of the parameters, the discounted expected benefits from mitigation will change. In general, higher values of *d* and/or smaller values of *p* and *T* will cause benefits to decrease. If the cost of retrofitting the bridges were set at $30 per square foot, then the net present value would be exactly 1. Any time that this cost was less than $30 it would be beneficial to retrofit the bridge. Of course, from a societal point of view, it would be beneficial to retrofit the bridge if the cost per square foot exceeded $30. There would be additional benefits to residents who use the bridges to commute to work or for pleasure, businesses using the bridges to move goods, and avoidance of business interruption due to loss of the transportation network. These additional benefits of mitigation are due to the reduction in time to repair the damaged bridges.

Step 5: Choose the Best Alternative

The criterion used by CBA is to maximize net present value (NPV) of societal benefits or minimization of the total societal costs. In the above example, with the expected costs equal to the benefits of $30 per square foot, retrofitting the bridges (A2) would be preferable over maintaining the status quo (A1).

In addition to the maximization of social benefits, there may be equity considerations that play a role in the evaluation of different alternatives. For example, if there were concerns by taxpayers on how much extra they would have to pay for tolls over the bridges to reflect the extra expenditures of retrofitting the bridges, then this may impact on the implementation of A2 even if it was deemed cost-effective using maximization of NPV as a criterion.

In essence, the choice of an optimal alternative is based on a set of assumptions that need to be carefully examined. In particular, one will want to undertake a set of sensitivity analyses to determine how robust the proposed solution is. For example, if the expected cost of retrofitting the bridges were only $15 per square foot, then there would be little doubt that mitigation would be a cost effective one. The reasoning is simple. The benefit-cost ratio for this problem would be (30/15), which is 2. Even if the estimates of the benefits of mitigation were off by a factor of 2, one would still want to retrofit the bridges if the cost of this measure is $15 per square foot.

Mitigation of Lifelines in Tennessee and California

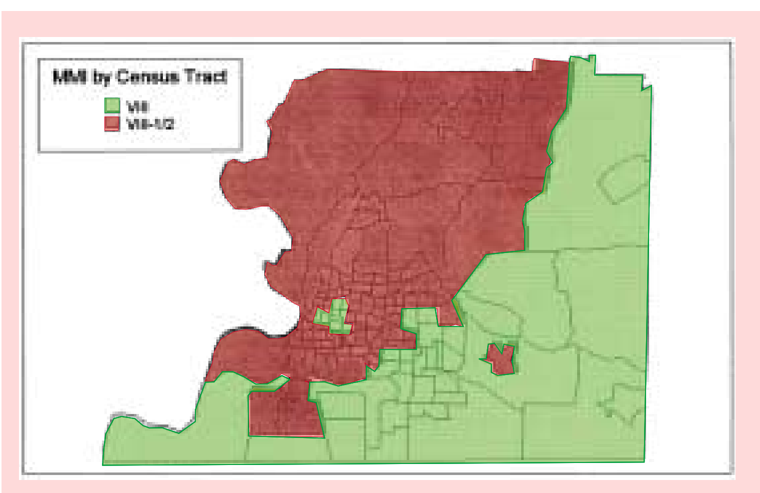
We now turn to the two case studies of lifeline systems to illustrate how one would compute the benefits and costs of mitigation: an electric power system in Shelby County, Tennessee and a water distribution system in Alameda and Contra Costa counties, California. The impacts of an earthquake on these lifeline systems include a wide range of direct and indirect losses. Our focus is on two types of losses to two different stakeholders: (1) the impact of interruption of service on business operations and the resulting losses in gross regional product (to Shelby County) and (2) loss of service to residential customers and the need to relocate individuals and entire families to temporary shelters (in Alameda and Contra Costa counties).

In these analyses, we consider only these two limited impacts of earthquake loss. Other impacts, such as the costs associated with fire following an earthquake, are not considered here. For the total loss to the water distribution system in Alameda and Contra Costa counties, we refer the reader to the study completed for the East Bay Municipal Utility District (Homer and Goettel, 1994).

Mitigation of an Electric Power System in Shelby County, Tennessee

As a continuation of an analysis done by researchers at MCEER (Shinozuka et al., 1998), we developed a framework to look at the cost-effectiveness of mitigation to the electric power system of the Memphis Light, Gas, and Water Division (MLGW) of the Memphis, Tennessee area. Loss to the gross regional product (GRP) of the different business sectors in the region due to loss of power is considered.

Figure 2 depicts a map of the Memphis/Shelby County area with indicated Modified Mercalli Intensity (MMI) impacts by census tract for a M = 7.5 earthquake. The Shelby County area is at risk from seismic activity in the New Madrid Seismic Zone (NMSZ) of the Central United States. This seismic zone lies within the central Mississippi Valley, extending from northeast Arkansas, through southeast Missouri, western Tennessee, western Kentucky to southern Illinois, and whose center is located to the northwest of Memphis. The NMSZ has a history of earthquake activity, with the largest earthquakes recorded in 1811-1812, and thus, it is an interesting case study for potential earthquake damage.



■ Figure 2. Shelby County, Tennessee (NCEER Bulletin 1996) 2

For this analysis, we used a M = 7.5 earthquake with an epicenter in Marked Tree, Arkansas, situated fifty-five kilometers northwest of downtown Memphis. We looked specifically at mitigation that could be undertaken on electric power systems, basing this study on a network of electric power serviced by Memphis Light, Gas and Water (MLGW). We examine the loss of serviceability of the electric power system from the scenario M = 7.5 earthquake, based on data developed by Chang (See Shinozuka et. al, 1998). We should note that damage to the overall system reliability was estimated using Monte Carlo simulation techniques, and with this damage, loss of service to different service zones was estimated. The focus of this research is how to use this output from the simulation analysis to look at the cost-effectiveness of mitigation.

Electric power is absolutely crucial in maintaining the social systems of a city, directly affecting businesses that cannot operate without it. The study of mitigation for the gas, power and water distribution systems is not studied here. For an update on the damage and loss to the water distribution system, see Chang et al. (2000).

Mitigation in this case is a seismic retrofit of a component of the electric power substation. Specifically, the transformers, used within the substations of the network to convert power, are retrofitted to withstand lateral loading. Tying down the wheels on the track can significantly improve the sliding movement and reduce the chances that these large, critical structures will overturn.[3]

The estimation of loss to the businesses in the area, due to service interruption, is calculated using the direct economic loss methodology from ATC-25 and modified by Chang to accommodate the importance factors specific to the Memphis area. The initial loss, L_j, to business sector *j* in the region directly following earthquake is estimated by equation (1).

$$L_j = (1 - a) \cdot g_j \cdot F_j \qquad (1)$$

In the above equation, *a* is the initial availability to the area. In other words, it is the percentage of customers receiving service immediately after the earthquake. *gj* is the gross regional product (GRP) in the region for the business sectors, *j*. In our case, *j* includes ten separate sectors. Examples include agriculture, construction, manufacturing, and services. The GRP was developed using data from the U.S. Census Bureau. Finally, *Fj* is the importance factor of the business sector, described as the percentage of production in sector *j* that would be lost if electric power service were completely disrupted (ATC-25, 1991).

For the scenario earthquake event, suppose restoration time is *T* days. So, the loss of production over *T* days, *LT*, is addressed by equation (2).

$$L_T = \sum_{t=0}^{T} L_j * \frac{(T - t)}{T} \qquad (2)$$

In this simplified analysis, if the transformers are seismically retrofitted, then we assume the loss of serviceability will be reduced, since some or all of the transformers would be functional after the earthquake. After knowing the difference in the number of functional transformers before seismic retrofit and after the retrofit scheme, one can then compute the savings to the business sector. In other words, the reduction in electric power outage characterizes the benefits of mitigation should the scenario earthquake occur in the service area. The *expected* benefits of mitigation are calculated by multiplying these benefits by the probability of the earthquake (*p*) and discounting over the relevant time horizon (*T*) that the transformer is expected to be in use (i.e., step 4 in the cost-benefit analysis).

To illustrate the type of CBA that could be undertaken, consider the following illustrative example. Assume that the cost of retrofitting each transformer is $10,000. If all 60 transformers in the electric power system are retrofitted, there is a one-time total cost of $600,000. Therefore, there are two alternatives: the status quo and retrofitting all the transformers for an upfront cost of $600,000. The stakeholders in the analysis are the businesses in the area needing electric power for production output. The benefits of mitigation are the reduction in restoration time due to more transformers functional following the earthquake event.

Additionally, we assume that the electricity system will last for 50 years and an 8% annual discount rate is used to compute the expected benefits over the 50-year horizon from retrofitting the transformers. We consider an earthquake of M = 7.5 would occur in the region once every 500 years, estimated from a study done by the USGS (Atkinson et al., 2000).

Figure 3 depicts the sensitivity of the CBA to restoration times of the electric power system would be reduced by either 1, 3 or 5 days. The figure is designed to show how CBA can be utilized to evaluate whether or not mitigation of certain parts of the system is cost-effective to certain stakeholders in the analysis. In this example, retrofitting transformers can be seen to be beneficial (i.e., the benefit-cost ratio is greater than 1) for a time horizon *T* greater than 13 years when restoration of the power system is reduced by five days and for *T* greater than 23 years when restoration is reduced by three days. Retrofitting the transformer is not cost-effective for any *T* when restoration of the power system is only one day. This is important to note because after the Northridge earthquake in 1994, electric power (LAPWD) was restored to ninety-percent of the users within one day. But, in the Chi-Chi, Taiwan earthquake in 1999, it took longer to restore power, with rolling blackouts to the northern part of the island for a week or more.

This analysis should be viewed as illustrative rather than definitive, since it is highly dependent on the assumptions made regarding the costs of retrofitting and the business interruption savings as well as the discount rate, *d*. For example, if *d* were four percent, then retrofitting the transformers would be even more attractive than under the current analysis.

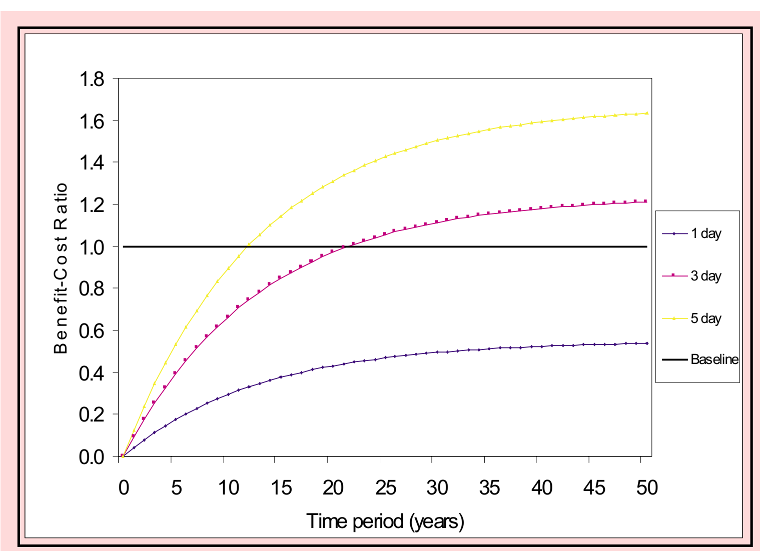


Figure 3. Illustrative Example of Effects of Electricity Lifeline Mitigation

Mitigation of a Water Distribution System in Alameda and Contra Costa Counties, California

The East Bay Municipal Utility District (EBMUD) is the public utility that provides potable water service to Alameda and Contra Costa Counties in northern California. We utilized information from the EBMUD Seismic Evaluation Program Final Report (Homer and Goettel, 1994), an intensive study of the East Bay water system that developed mitigation initiatives that will be completed during their Seismic Improvement Program. Our analysis focuses on the mitigation of 172 water storage tanks in 120 of the 122 EBMUD pressure zones.

To conduct this analysis, four scenario earthquake events were chosen for analysis, based on the completed EBMUD report (Table 1). These events represent the maximum plausible earthquake event that could occur on any given fault, with the exception of the Hayward

M = 6.0. For the Hayward fault, an earthquake of magnitude M = 6.0 is the most probable event and M =7.0 is the maximum plausible event.

In this analysis, there are two alternatives: the status quo and the mitigation of the water storage tanks.Those affected by the disruption of the water supply system are the residents in the service area that may be forced to relocate to temporary shelters for a period of days or even weeks.The direct cost of retrofitting the water tanks is based on data supplied by the EBMUD and given in Table 2.

■ Table 1. Scenario Events

Fault Name	M	Description
Hayward	7.0	event ruptures 50 to 60 km long segment of fault
Hayward	6.0	event ruptures an 8 to 13 km long segment of the fault
Calaveras	6.75	event ruptures the northernmost part of the known active fault
Concord	6.5	event occurs along this fault east of the EBMUD service area

Loss of Serviceability and Effects on Residential Displacement

The benefits of mitigation are the losses resulting from loss of water service to residential customers with and without the seismic upgrade of the tanks. When water service is disconnected from a place of residence, the individuals who live in these buildings will be forced to find alternative shelter until water service is restored. In the event of an earthquake, the potable water system can be damaged to an extent that water service may not be restored to an area until many weeks following the event. Figure 4 details our methodology for estimating the costs that are associated with these displaced individuals.

First, we determined the likelihood of tank failure in each pressure zone. EBMUD performed a detailed analysis of their system, us-

■ Table 2. Direct Cost to Retrofit Water Tanks

Tank Size	Seis. Upgrade Cost [1]	Partial Loss: Cost to make 'operational' after EQ. No upgrade prior to EQ" [2]	Partial Loss: Repair time for upgrade to make 'Operational' after EQ	Full Loss: Install Temp. Bolted Steel Tank for "Operational Restoration" [3]	New Tank Cost: Steel Replacement [4]	Full Loss: Replace Tank with Equivalent size tank
Concrete						
0.5	$ 500,000	$ 150,000	6 weeks	10 weeks	$ 1,000,000	1 year
1	$ 600,000	$ 150,000	7 weeks	10 weeks	$ 1,500,000	1 year
1.5	$ 750,000	$ 150,000	7 weeks	10 weeks	$ 1,750,000	1 year
2	$ 900,000	$ 200,000	8 weeks	10 weeks	$ 2,000,000	1 year
3	$ 1,200,000	$ 200,000	8 weeks	10 weeks	$ 2,500,000	1 year
5	$ 1,500,000	$ 200,000	9 weeks	10 weeks	$ 3,000,000	1 year
Steel						
0.25	$ 100,000.00	$ 50,000	1 week	10 weeks	$ 650,000	1 year
0.5	$ 200,000.00	$ 50,000	1 week	10 weeks	$ 1,000,000	1 year
1	$ 250,000.00	$ 50,000	1 week	10 weeks	$ 1,500,000	1 year
3	$ 300,000.00	$ 70,000	2 weeks	10 weeks	$ 2,500,000	1 year
5	$ 400,000.00	$ 70,000	2 weeks	10 weeks	$ 3,000,000	1 year

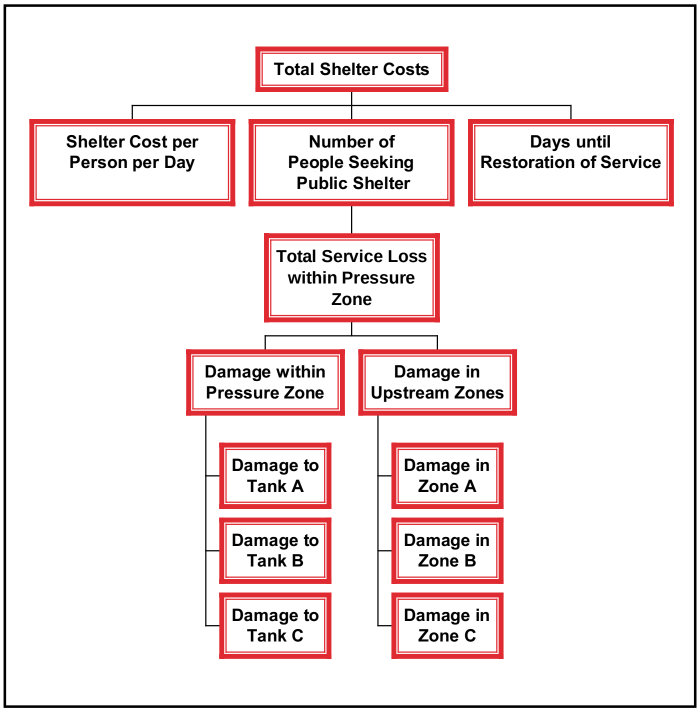
Footnotes:

1 Includes non-seismic upgrades, which are approximately 15% of seismic costs.

2 Partial loss for steel tank due to damaged valve pit piping. Time due to valve replacement. The tank structure assumes to either fully survive or fully fail.

3 The existing tanks may be out of service for this period of time; however, if there are multiple reservoirs in a pressure zone, the business interruption will likely be a much lesser time than indicated. Assume temporary replacement with either a .28 MG or 0.4 MG tank.

4 Cost includes: demolish existing tank, valve pit modification, metal appurtenances, miscellaneous site work, water quality piping, 15% construction contingencies.



■ Figure 4. Cost to Shelter Displaced Residents from one Pressure Zone

ing their own system risk analysis software, SERA. Ten simulations of each of the four above earthquakes (i.e., forty simulations in all) were run to determine the extent of damage that their system is expected to face following an earthquake. For each simulation, tanks were said to fully fail, partially fail, or not fail. Our analysis of expected loss consists only of two of these three states – full failure and no failure – since we have no means by which to accurately analyze the complex network effects of partial loss. Therefore, if a tank was said to fully fail in 6 of 10 Hayward M 7.0 scenarios, then we say there is a 60% chance of full tank failure following a Hayward M 7.0.

Next, determination of likely water service within individual pressure zones was calculated. Some pressure zones are served by more than one tank, and therefore, the overall loss of service in a pressure zone is a combination of the effects of individual tanks in the pressure zone failing. The loss to pressure zone one, L_{PZ1}, therefore, can by defined by equation (3). In the equation, A_{N1} is the probability of full loss for a tank in pressure zone one and N1 is the number of tanks in zone one.

$$L_{PZ1} = \sum_{t=0}^{N} \frac{A_{N1}}{N1} \qquad (3)$$

Although a pressure zone may experience loss of service due to failure of its internal tanks, it may also experience service interruption if pressure zones that provide water to its tanks experience failure. To fully understand the total loss within a zone, we must take this into consideration as indicated by equation (4):

$$P_1 = (X_1 \cdot X_2 \cdots X_n) + [1 - X_1 \cdot X_2 \cdots X_n] \cdot L_{PZ1} \qquad (4)$$

In equation (4), P_1 is the percentage of customers in pressure zone one that will be without service following an earthquake, X_1 through X_N represent the probability of failure in pressure zones that feed into pressure zone one, and L_{PZ1} is the loss due to tank failure in pressure zone one. If every pressure zone that provides water to the tanks in pressure zone one fails, then no customers in pressure zone one will have service. The probability that this occurs is represented by the product of the probabilities that each individual precedent pressure zone will fail. If any or all of these precedent pressure zones has service, however, we will assume that the district will be able to provide enough water to its tanks in pressure zone one so that customers have their minimum water demands met. Then, the only residents without water service will be those represented by L_{PZ1}, or those who do not have service due to tank failure within pressure zone one.

Once the overall service to each pressure zone is calculated, the number of people displaced and seeking temporary shelter can be determined. Since we are analyzing 120 pressure zones in the system, the number of people seeking temporary shelter following an earthquake is as follows:

$$R_S = \sum_{z=1}^{120} u_z \cdot P_z \cdot n_{hz} \cdot s_z \qquad (5)$$

In equation (5), R_s represents the number of residents seeking temporary public shelter following a disaster and u_z is the number of occupied housing units in pressure zone z. This is found by overlaying U.S. Census data on the service district. P_z is the percent of service loss in pressure zone z, or the percentage of housing units without water service, and n_{hz} is the number of people per housing unit in zone z. This is calculated by dividing the total population in zone z by the total number of occupied housing units. Finally, s_z is percentage of displaced residents in zone *z* who well seek shelter in a public facility. This is determined by inputting U.S. Census tract demographic information into a methodology developed for HAZUS (NIBS, 1997)[4]. This analysis is run for each of the districts 120 pressure zones considered, then aggregated to determine the total number of residents across the district who will seek shelter following a disaster.

To determine the total cost of sheltering residents displaced by loss of potable water service to their home following the earthquake, we multiply R_s by $11.50. This value is based on an American Red Cross estimate of between $10 and $13 to shelter a person for a single day (Red Cross, 2000).

Finally, to determine the total aggregate displacement costs following an earthquake, we must first consider whether the per-day costs will remain constant over time. We assume that if a tank is fully damaged it will not be able to supply water to any of its customers until it is fully repaired, or until a replacement tank can be acquired. Therefore, there will be no incremental increase in service over time and the per-day total costs of sheltering residents will remain constant over that period (since people are not able to return home). Based on this assumption, the total cost to shelter displaced residents following an earthquake is easily calculated by multiplying the total cost per day by the total time until restoration of service. In this case, we assume ten weeks or seventy days, based on information provided by EBMUD.

Note that the above analysis characterizes the impact on shelter costs under the assumption that the status quo was being maintained. The alternative option is to retrofit the water tanks in some of the pressure zones in Alameda and Contra Costa counties. By undertaking this protective measure, one reduces the chances that one or more of the tanks will fail and hence, disrupt water service for some period of time. The benefits of this mitigation measure will be determined by the reduction in restoration time for water to residences in the area affected by the earthquake.

One also needs to take into account whether individuals were forced to evacuate their homes because there was severe structural damage due to the earthquake. Suppose one is evaluating the benefits of retrofitting water tanks to residents in the area. Then one should eliminate any homes where evacuation would be required even if the was no disruption of water. Otherwise, one would be overstating the benefits from retrofitting the water tanks in the East Bay area.

This analysis of the residential sector in the East Bay area illustrates the type of calculations one would make to evaluate the expected benefits of mitigation. Turning to business interruption losses from an earthquake, a similar analysis to the one in Shelby County is being undertaken with EBMUD in northern California to evaluate the impact of mitigation on this sector. Combining both the residential displacement costs and business interruption, one could undertake a more comprehensive CBA, determining under what circumstances the proposed mitigation will be most cost-effective.

Making CBA Useful for Policy Analysis

The above examples are only illustrative as to how CBA can be used, rather than how it is actually applied to either Shelby County, Tennessee or Alameda and Contra Costa counties, California. For CBA to be a useful tool for policy analysis in a specific region, one must have the most accurate data available for the analysis and keep the interested parties' priorities in mind. For this reason, we have been working very closely with personnel at EBMUD to ensure that our analysis of their water supply is a meaningful one.

Our intention is to undertake a sufficiently rich analysis of how mitigation can be utilized for particular lifeline systems, such as the EBMUD water distribution system. Unless key decision makers can appreciate the role CBA can play in determining whether to implement specific mitigation measures, this methodology may have some theoretical interest but no practical importance.

The task of making CBA a useful methodology is a challenging one. It requires bringing together scientists and engineers with social scientists to analyze a problem. It requires one to articulate the nature of the uncertainties associated with the recurrence interval of earthquakes of different magnitudes, as well as the confidence intervals surrounding the expected benefits and costs of different alternative strategies. In a nutshell, it requires the integration of science with policy.

The data and techniques are now available to undertake this type of integration with respect to earthquake mitigation. The challenge is to present the analyses to decision makers so they are willing to defend the proposed recommendation because it makes economic sense to them while satisfying their political concerns. Cost-benefit analysis provides a framework for accomplishing this important task.

Endnotes

[1] Of course, the public utility or private sector organization operating the lifeline facility may raise its rates to reflect the additional cost of the mitigation measure. In this sense, all the users of the facility bear the costs of loss prevention.

[2] http://mceer.buffalo.edu/publications/bulletin/96/02/apr96nb.html.

[3] This type of mitigation was chosen, based on discussions with Masanobu Shinozuka and insight from the annual MCEER conference in November 1999.

[4] This methodology does consider that a proportion of displaced residents will stay with friends or family rather than seek publicly-funded shelters.

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