Life Cycle Cost Analysis with Natural Hazard Risk:
A Framework and Issues for Water Systems

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Abstract

This paper addresses the problem of identifying optimal seismic risk reduction strategies for the intelligent renewal of civil infrastructure systems through the application of life cycle cost analysis. An optimal strategy is defined as one which minimizes total life cycle costs, including repair and user costs associated with damage in natural disasters, subject to meeting the stated performance objective for the system. Particular attention is paid to issues for water delivery systems. An extended life cycle cost framework is developed and demonstrated with numerical examples using a simple hypothetical water system.

I. Introduction

The application of the life cycle cost concept represents an important framework for management of existing infrastructure systems. Life cycle costs include not only the initial cost of construction, but also costs associated with maintenance, retrofit, and upgrading that are anticipated over the life of the system. While the concept itself is not new, and its application to infrastructure management in the U.S. has been growing (e.g., in bridge management systems), researchers have only begun to explore its applicability to problems of natural hazard risk.

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Life cycle cost analysis, as currently applied to infrastructure systems, typically neglects the cost associated with damage in natural disasters. As infrastructure systems age, they become increasingly vulnerable to damage in natural disasters due to progressive deterioration of physical condition. While hazard-related losses for a given infrastructure system are subject to great uncertainty, events such as the 1994 Northridge and 1995 Great Hanshin (Kobe) earthquakes have shown that they can potentially be severe and should be addressed within the context of intelligent renewal of civil infrastructure systems, at least in regions of high seismicity.

This paper develops an application of life cycle cost analysis to the management of natural hazard risk, particularly earthquake hazard, for infrastructure systems. It extends the traditional life cycle cost framework to include both the cost of seismic upgrading prior to a disaster and the expected repair costs from damage in earthquake disasters. The economic costs imposed on users from lifeline service disruption are also included. Previous studies have shown that for lifeline systems, user costs or losses can vastly outweigh the costs of physical repair to the system -- in the case of water systems, by as much as 10 times (Chang et al., 1996).

In this context, this paper explores issues in the application to water delivery systems. Particular attention is paid to utilizing life-cycle cost analysis for meeting long-term system performance objectives for earthquake hazard. One problem with seismic upgrading programs such as pipeline replacement programs is that they are often prohibitively expensive in the face of limited capital improvement budgets. However, the integration of seismic vulnerability criteria with routine maintenance and capital improvements plans provides a potentially attractive alternative to considering seismic retrofit independently. Section II provides some examples of how seismic upgrading can be integrated with other infrastructure management decisions based on the experiences of selected utility companies in the Western U.S. and Japan.

Section III develops the life cycle cost analysis framework for risk management that captures the basic tradeoff between seismic upgrading costs and benefits. It extends a basic framework outlined in Chang and Shinozuka (1996) by accounting for features of network systems in general and water delivery systems in particular, as well as by incorporating system seismic performance objectives. Section IV illustrates how this framework can be applied to support risk reduction decision-making in infrastructure systems management. The problem is posed as one of determining the optimal means for improving the seismic safety of an existing infrastructure system, where the “optimal” solution is defined as one that simultaneously meets the seismic performance objective and minimizes life cycle costs. Numerical examples using a simple, hypothetical water delivery system are provided. Section V concludes and identifies areas for further research.

II. Issues for Water Systems
While life cycle cost analysis may be used to evaluate decisions for new design or routine pipeline and other facility upgrading, water utilities often do not conduct such detailed analysis for evaluating seismic risk reduction projects. However, there are many examples where upgrade projects integrate mitigation of seismic deficiencies with other system needs.

The Kobe Water Department had an aggressive pipeline replacement program prior to the 1995 Kobe Earthquake. They had nearly completed replacing the asbestos cement pipe in the system, and were well on their way to replacing all the cast iron pipe in the system. At the time of the earthquake, nearly 90% of the pipe in the system was either ductile iron or steel. The reason for replacing the pipe was not for seismic vulnerability issues, but to reduce system maintenance and improve general reliability. In the Kobe Earthquake, the ductile iron pipe had unit failure rates of one-third that of cast iron. In the case of Kobe Water, replacement of pipe for maintenance reasons had unplanned benefits.

The Portland, Oregon, Water Bureau conducted a seismic vulnerability analysis of the groundwater emergency water supply system. One of the findings was that one of the main groundwater collection pipelines was constructed of segmented concrete cylinder pipe, and located in an area subject to significant earthquake liquefaction-related lateral spread. Replacement in a less vulnerable alignment using less vulnerable pipe was recommended. The project will likely proceed because the pipeline also has inadequate capacity to move water from the wells in that area of the system to the groundwater pump station. Replacing the line will mitigate its earthquake vulnerability and increase system capacity.

The Lakehaven Utility District, serving about 90,000 people in Federal Way, Washington, evaluated the vulnerability of their steel reservoirs. Four of the reservoirs had a high probability of failure in the design earthquake. The district proceeded with upgrade of three of the reservoirs. A decision was made not to upgrade the fourth reservoir because it no longer played a key role in system operation. It was substantially smaller than the other reservoirs, and the function it provided could be provided by a larger newer reservoir located nearby. The cost to upgrade the reservoir exceeded the expected benefit.

The City of Bellevue, Washington, a suburb east of Seattle with a population of approximately 100,000 people, conducted a seismic vulnerability assessment of their water system. Among other findings, the study identified a key transmission line located in an area of unstable soils. The pipeline had a high maintenance history, and would be expected to fail in an earthquake. Two alternatives were considered, 1) install an earthquake valve system to isolate the line in the event of an earthquake, and 2) replace the line with less vulnerable materials. If the pipeline were isolated, water could be temporarily routed through alternative lines to maintain a limited level of service. The big advantage was that it would keep the system from draining through the failed pipeline. The disadvantage of the earthquake isolation valve system was that it might only be used once a century, or more, but would have to be maintained over that period. If the pipeline were replaced, it would significantly reduce both maintenance and earthquake vulnerability. The “new” pipeline would
reduce maintenance on a continuing basis, as well as be more reliable in an earthquake. The disadvantage of the new pipeline was that it may still fail if large permanent ground deformations were experienced. The city selected the new pipe alternative.

The Greater Vancouver Water District, GVWD, serving the Vancouver metropolitan area in British Columbia, is improving their east to west transmission capability for two reasons: 1) the need for additional water available from their Coquitlam supply, northeast of the system, and 2) the transmission systems from the other two supplies are vulnerable to earthquake. The GVWD’s supply comes from three watersheds. Starting from the west, they are Capilano, Seymour, and Coquitlam. Transmission lines from the first two supplies pass through highly liquefiable areas both on land and under the Burrard Inlet. Mitigation would be very expensive, and repair following an earthquake, particularly underwater, could take a long time. Currently, the capacity of both of these supplies is fully used during peak demand periods. Additional capacity is available from the Coquitlam supply. By constructing a new east to west transmission system, the GVRD is both increasing capability to use the Coquitlam supply and mitigating system earthquake vulnerability.

The Marin Municipal Water District (MMWD) serving about 250,000 people in the area immediately north of the Golden Gate Bridge near San Francisco, California, conducted an integrated water system reliability study. The region had suffered from the Loma Prieta Earthquake in 1989. As a result, several of the region’s major water utilities had conducted extensive earthquake mitigation programs. Further, in 1991, the Oakland Hills fire across San Francisco Bay from Marin had killed 25 people and destroyed over 3,000 single family houses with total losses exceeding $1.5 billion. The MMWD wanted to be prepared if/when either of these hazards were encountered in their service area. The objective of the study was to identify system components that were vulnerable to earthquakes and/or deficient in providing adequate water for fire suppression. The study resulted in a long list of recommended improvements and led to passage of an $80 million bond issue to implement them. While many of those improvements focus on either earthquake performance or water for fire suppression, some provide mitigation for both concerns.

These examples demonstrate a number of issues for water systems that should be considered in a life cycle cost framework: (1) the importance of quantifying cost tradeoffs for mitigation options; (2) the significance of collateral benefits (e.g., maintenance cost or capacity expansion) in the cost/benefit equation; and (3) the variety of performance objectives that might be appropriate for a particular system. The following section incorporates these issues in presenting a life cycle cost framework that addresses natural hazard risk.

III. Expanded Life Cycle Cost Framework
Total life cycle costs associated with an infrastructure system such as a water delivery system can be classified into four principal types: planned and unplanned costs accruing to the system owner ($C_I$ and $C_3$, respectively), and associated user costs for the two categories of owner costs ($C_2$ and $C_4$, respectively). Here, planned owner costs include expenditures for system construction ($C_I$), maintenance ($C_M$), and any seismic retrofit ($C_S$) for elements $p$ (e.g., pipe) in the system. Unplanned costs here refer to the consequences of natural disaster, specifically earthquakes. User costs pertain to the economic loss imposed on users from disruption of infrastructure services. In the illustration developed below for an existing water system, new construction costs $C_I$ are omitted. Only user costs associated with service disruption in natural disasters are considered; routine maintenance and retrofit are assumed to cause negligible user disruption ($C_2=0$) because outages would be planned and short-term. Total life cycle cost $C$ is the sum of costs in each time period $t$ discounted to the present value by a factor $z$ that is based on a discount rate $i$ indicating the expected market rate of return on an investment. Annual maintenance costs $m$ at time $t$ depend upon the physical properties $x_p$ of the system element; for example, deterioration rates and associated maintenance needs may vary according to pipe material, corrosiveness of local soil conditions, etc. Seismic retrofit costs $s$ in the illustration below, which may be planned for any time $t$, pertain to pipe replacement and depend upon the properties of the new pipe being installed. Thus total life cycle costs can be summarized as:

$$C = C_I + C_2 + C_3 + C_4 \quad (1)$$

and planned costs as:

$$C_I = C_I + C_M + C_S \quad (2)$$

$$C_M = \sum_t \sum_p m_p(t,x_p) z(t) \quad (3)$$

$$C_S = \sum_t \sum_p s_p(t,x_p) z(t) \quad (5)$$

Unplanned costs associated with damage from earthquakes is expressed in probabilistic terms to reflect the local seismic hazard. Expected repair costs associated with damage in an earthquake derive from a probabilistic condition/performance index $G_p$ evaluated for and summed over each element $p$, damage state $k$, and time period $t$, multiplied by the associated unit repair cost $r$ for the damage state and discounted to the present value.

$$C_3 = \sum_p \sum_k G_p(x_p,d_k,t) r_k z(t) \quad (6)$$

The element condition/performance index $G_p$ is specified as a probabilistic factor that changes over time due to natural deterioration, as well as the mitigative (condition-
improving) effects of maintenance and seismic retrofit activity. That is, in the initial
time period, the index represents a convolution of the local hazard curve \( Pr(h) \) with
the element’s fragility curve \( Pr(d_k \mid h) \) for each damage state \( d_k \) over all levels of the
hazard \( h \), measured for instance in terms of peak ground acceleration (PGA). In
subsequent time periods, this index increases or decreases through a natural
deterioration factor \( w_n \), maintenance factor \( w_m \), and seismic retrofit factor \( w_s \) that
represent changes in the element’s physical condition.

\[
G_p(x_p,d_k,t) = Pr(d_k \mid x_p,t) = G_p(x_p,d_k,t-1) \{1 + w_n(x_p,t) - w_m(p(x_p,t)) - w_s(p(x_p,t))\} \tag{7}
\]

where

\[
G_p(x_p,d_k,0) = Pr(d_k \mid x_p,t=0) = \int_h Pr(d_k \mid x_p,h) \cdot Pr(h) \tag{8}
\]

In contrast to the owner costs associated with earthquake damage, the user
costs \( C_4 \) are related to the resulting infrastructure service disruption, rather than the
amount of repairs that need to be made. User costs are modeled in relation to a
performance index at the service area level. In the case of certain lifelines such as
electric power, service areas can be naturally defined in terms of the customers served
by a particular substation. For water delivery systems, census tracts or larger
agglomerations may represent meaningful service areas. In the illustration below, the
performance index \( G_a \) for each service area \( a \) for the \( j \)th areal performance level \( L_j \)
is determined on the basis of network hydraulic analysis for simulated earthquakes at
each time \( t \). Total user cost consists of the discounted sum over all \( t \) and \( j \) of the areal
performance index multiplied by the disruption factor \( b_d \) for the damage state \( 0 \leq b_d \leq 1 \) and a unit user cost \( u \) for the area.

\[
G_a(L_j,t) = Pr(L_j \mid t) \tag{9}
\]

\[
C_4 = \sum_t \sum_j \{G_a(L_j,t) \cdot b_d(j) \cdot u_a(t)\} \cdot z(t) \tag{10}
\]

Equations (1) through (10) above describe the estimation framework for life
cycle costs and total life cycle costs \( C \) can be optimized over a specific set of
parameter values. However, for purposes of seismic risk management for an
infrastructure system, the optimization of life cycle costs over a range of seismic
retrofit alternatives, for example, should relate to some performance objective or
criteria related to the system as a whole. Defining a system performance index \( G_s \),
based on the performance indices \( G_a \) for the various service areas at any given time \( t \),
a minimum allowable system performance level \( S \) can be specified that serves as a
constraint on the life cycle cost optimization problem.
\[ G_s(t) = G_s(G_a(L_j, t)) \quad \text{for all } a, j \quad (11) \]

\[ G_s(t) \geq S \quad \text{for all } t \quad (12) \]

The exact definition of the areal and system performance levels and system performance criteria depend upon the system being studied and the objective of the analysis, as will be demonstrated through numerical examples in the following section.

IV. Numerical Examples

**Hypothetical Water Delivery System**

To illustrate the framework above and demonstrate its applicability to seismic risk management for infrastructure systems, numerical examples are developed for a simple hypothetical water delivery system. As shown in Figure 1, this network consists of 9 nodes and 11 links or pipeline segments. Node 1 is a supply source not subject earthquake damage. Nodes 2 through 6 are demand nodes providing water to the region. Nodes 7 through 9 are dummy nodes that serve only to indicate a change in local ground condition between adjoining pipe segments. The region or city consists of four service areas (A through D), each of which is served by one or two demand nodes as indicated. A river runs through areas B and D, which are consequently subject to high liquefaction hazard. Area A is the commercial core of the region, while B and C are primarily residential; however, B also contains a critical industrial facility. Area D was developed somewhat later than A through C and is a new residential area. Links 1 through 8, being part of the originally developed system, consist of unlined cast iron pipe that is at the current time 30 years old. Links 9 through 11 consist of less seismically vulnerable cement-lined ductile iron pipe that is 10 years old. The system is gravity-fed from Node 1, so there are no pump stations.

**Performance Level Definitions and Criteria**

For present purposes, three service area performance levels and four system performance levels are defined, as shown in Table 1. These definitions were adopted for simplicity and should be refined in future study. For example, in addition to the flow ratio criteria used here, that is the ratio of post-earthquake to normal flow at nodes in the service area, areal performance could also consider water pressure to reflect fire-fighting capacity. Note that with this performance classification, Level 1 represents best performance, so that the constraint in equation (12) should be \( G_s(t) \leq S \).

System performance levels were defined based on guidelines published by the American Water Works Association (AWWA) in which the following performance objectives are suggested: in a design basis (475-year return period) earthquake, that pipeline failures result in a service loss to no more than 30 percent of the area and are repaired within 7 days; and in an operating basis (72-year return period) earthquake,
that incidental pipeline failures affect less than one percent of the system and are repaired within 24 hours (Ballantyne, 1991). Note that the system performance levels in Table 1 are operationalized specifically for the example with four service areas.

In this illustration, we are interested in minimizing system life cycle costs while achieving acceptable seismic performance through retrofit. The performance criteria constraint to the optimization problem is that the system meet the AWWA suggested performance objective, that is perform at Level 3 or better in a design basis earthquake. We further stipulate that this criteria should have at least a 70 percent chance of being met.
Seismic Hazard and Performance Simulation

The seismic hazard curve for this example was approximated by three events: an operating basis earthquake (OBE) with 72-year return period, or 50 percent chance of exceedence in 50 years, an “intermediate” basis earthquake (IBE) with 250-year
return period, and a design basis earthquake (DBE) with 475-year return period, or 10 percent chance of exceedence in 50 years. The associated peak ground acceleration levels are assumed to be 0.15g, 0.25g, and 0.30g, reflecting a moderate level of seismicity. For simplicity, ground shaking intensity is also assumed to be the same throughout the study area, neglecting such factors as differences in site amplification or attenuation with increasing distance from the earthquake source.

The seismic performance of the system and its elements were modeled using a software program, LIFELINE-W(II), developed at Princeton University by M. Shinozuka and colleagues. This program has been previously applied to evaluating the seismic performance of an actual water delivery system serving Memphis, Tennessee (Shinozuka, 1994; Tanaka et al., 1997). For a specified network, it conducts flow analysis to evaluate normal water flow and pressure conditions, simulates damage from the earthquake, performs connectivity and hydraulic analysis on the damaged network, and compares post- with pre-earthquake conditions.

The current analysis considers damage only to pipes. Damage is estimated based on pipe fragility curves through a series of Monte Carlo simulations and averaged. Fragility curves differ according to pipe material and local ground condition. Although the program does not specifically model liquefaction-induced pipe damage, links in the hypothetical network that are susceptible to liquefaction were modeled as having “poor” local ground condition. Link 1 (to the supply source) was modeled as having “good” ground condition, while all other links were on “average” soil. The relationships between PGA and flow ratio for the damaged system at the 5 demand nodes (nodes 2 through 6) are shown in Figure 2. The flow ratio results plotted consist of the mean over 20 simulations. Figure 2 shows that nodes 3 and 6, serving areas B and D respectively, are the most vulnerable to service disruption, while node 2 retains full service even in an earthquake of up to 0.30g.

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Operationalization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Service Areas</strong></td>
<td></td>
</tr>
<tr>
<td>(1) Full service</td>
<td>Flow ratio (r \geq 67%)</td>
</tr>
<tr>
<td>(2) Partial service</td>
<td>(33% &lt; r &lt; 67%)</td>
</tr>
<tr>
<td>(3) No service</td>
<td>(r \leq 33%)</td>
</tr>
<tr>
<td><strong>System</strong></td>
<td></td>
</tr>
<tr>
<td>(1) Normal</td>
<td>No service area at Levels 2 or 3.</td>
</tr>
<tr>
<td>(2) Localized damage</td>
<td>No service area at Level 3 and 1-2 areas at Level 2.</td>
</tr>
<tr>
<td>(3) Critical</td>
<td>No service area at Level 3 and 3+ areas at Level 2; or 1 area at Level 3.</td>
</tr>
<tr>
<td>(4) Inadequate (does not meet AWWA 70% area/70% flow criteria)</td>
<td>2+ service areas at Level 3.</td>
</tr>
</tbody>
</table>

Table 1. Performance Level Definitions
Results from this program were first compared with expectations from expert judgment in terms of service area and system performance using the performance level definitions in Table 1. The outcome is shown in Table 2.

Table 2. Comparison of Flow Analysis Results with Expert Judgment

<table>
<thead>
<tr>
<th></th>
<th>Area A</th>
<th>Area B</th>
<th>Area C</th>
<th>Area D</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operating Basis Earthquake (OBE)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow ratio (from flow analysis)</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>Performance: - flow analysis</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>- expert judgment</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>“Intermediate” Basis Earthquake (IBE)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow ratio (from flow analysis)</td>
<td>1.00</td>
<td>0.25</td>
<td>1.00</td>
<td>0.51</td>
<td>-</td>
</tr>
<tr>
<td>Performance: - flow analysis</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>- expert judgment</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>Design Basis Earthquake (DBE)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow ratio (from flow analysis)</td>
<td>0.66</td>
<td>0.00</td>
<td>0.08</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Performance: - flow analysis</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>- expert judgment</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

In the OBE, the only difference occurs in Area B, where expert judgment predicted liquefaction-related damage to the cast iron pipe segments whereas the LIFELINE-W(II) program predicted very little damage. This may be because in the latter, liquefaction effects were approximated by using damage functions for “poor”
soil. This discrepancy is reflected in the difference in predicted system performance level (Level 1, or “normal”, versus Level 2, or “localized damage”).

On the other hand, system performance levels from flow analysis and from expert judgment are in agreement for the IBE and DBE (Levels 3, or “Critical”, and 4, or “Inadequate”, respectively). Areal performance levels for the liquefaction-prone areas B and D are also in agreement. However, in areas A and C, relative to expert judgment, the program predicts better performance in the IBE (Level 1, or “Full Service”, as opposed to 2, or “Partial Service”). In the DBE, program results agree with expert judgment for Area A (Level 2) but predict higher disruption in Area C (Level 3, “No Service”, as opposed to 2). While these discrepancies should be investigated further, they do not demonstrate a persistent bias in one direction.

Deterioration and Seismic Upgrading

With time, the physical condition of system elements is expected to deteriorate, leading to both increased maintenance costs and greater vulnerability to damage in a given earthquake. This effect is particularly important to capture when considering life cycle costs over some extended period of time. In the current example, a timeframe of 20 years is used for analysis. Annual maintenance costs \( m \) are assumed to increase in each year \( t \) according to a constant factor \( \delta \) that varies according to pipe material \( x \) for each link in the system, as follows:

\[
m(t, x) = (\mu(x) + \delta(x)t)M
\]

where \( \mu \) is the initial annual probability of having a leak and \( M \) is the unit cost of repairing a leak. In the absence of actual data, \( \mu = 10^{-4} \) was assumed for all pipe materials while \( \delta = 2 \times 10^{-4} \) was assumed for concrete-lined ductile iron pipe and \( \delta = 4 \times 10^{-4} \) for unlined cast iron pipe, which is expected to deteriorate at a more rapid rate. \( M \) was assumed to be 500 dollars.

To model the effect of deterioration on expected seismic performance, the LIFELINE-W(II) program was modified to include a deterioration factor \( w_n \) as shown in equation (7) above. This factor served to modify the probability of having at least one break for a given pipe, which is calculated from the program’s fragility curves. Furthermore, because the fragility curves are based upon empirical data from historic earthquakes, which in turn are based on pipes of various ages, it was assumed that these fragility curves are applicable to cast iron pipes up to 30 years old and ductile iron pipes up to 10 years old, respectively (reflecting changes in practice in pipe material usage in the U.S.). A reasonable value for \( w_n \) was judged to be 0.02, indicating that in each period, the annual probability of having at least one break for a given pipe (for a given earthquake) is assumed to increase by 2 percent.

The hypothetical example explores a number of seismic upgrading alternatives in the form of replacing existing pipe(s), in particular the older cast iron links, with less vulnerable new, ductile iron pipes. This entails four types of cost effects: first, \( C_I \) increases due to the expense of the upgrading (assumed to be 100
dollars per meter of new pipe). Second, maintenance costs decrease as the age or effective $t$ in equation (13) is reset to zero. Finally, both the expected earthquake-related repair and user costs ($C_2$ and $C_4$) also decrease as the deterioration factor $w_n$ is assumed to be zero for the first 10 years after the pipe replacement measure is undertaken. Clearly, for each potential pipe(s) replacement, the first cost is to some degree offset by the other three cost savings; however, the net effect on total life cycle costs will vary for the different seismic upgrading alternatives.

**Repair, User, and Total Life Cycle Costs**

Other extensions made to the LIFELINE-W(II) program included estimation of earthquake repair costs, associated user cost from disruption of service, and total life cycle costs. Repair costs were estimated based on the mean number of breaks from the 20 simulations for each earthquake and time period. An average of 1500 dollars to repair a break was assumed from expert judgment.

User costs were modeled by assuming a unit user cost of 300 million dollars. This represents annual gross regional product for the hypothetical region, 50 percent of which is produced in Area A, 30 percent in Area B, and 10 percent each in Areas C and D. For the disruption factors noted in equation (10) above, the following values were assumed: for areal Performance Levels 1, 2 and 3 respectively, $4 \times 10^{-4}$, $7.7 \times 10^{-3}$, and $3.85 \times 10^{-2}$. These factors are based upon findings from a previous study (Chang et al., 1996). Areal and system performance levels were estimated as shown in Table 1 for each simulation, and mean performance levels were computed for each earthquake scenario and time period.

Total life cycle costs were estimated by discounting and summing annual costs for maintenance, seismic upgrading, expected earthquake repairs, and associated user disruption over the 20-year study period. A discount rate of 5 percent was used.

**Results**

Life cycle cost results for the baseline case without seismic upgrading are shown in Table 3. Total costs amount to $3.144 million in present value terms, of which 89 percent represents maintenance costs. Earthquake damage repair costs amount to only 1 percent of total life cycle costs, while the associated user costs represent roughly 10 percent.
Table 3. Life Cycle Costs in Baseline Case

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>Cost (Discounted, $mil.)</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic upgrading</td>
<td>$ 0.000</td>
<td>0.0 %</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$ 2.798</td>
<td>89.0%</td>
</tr>
<tr>
<td>Earthquake damage repair</td>
<td>$ 0.034</td>
<td>1.1%</td>
</tr>
<tr>
<td>User</td>
<td>$ 0.312</td>
<td>9.9%</td>
</tr>
<tr>
<td>Total</td>
<td>$ 3.144</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Figure 3 shows the mean system performance level for the operating, “intermediate”, and design basis earthquakes in each year over 20 simulations. Performance levels increase (worsen) over time as pipe deterioration increases element and hence system vulnerability to earthquake damage. (Note that mean performance levels do not increase monotonically because annual changes in vulnerability are small and only 20 simulations were performed for each case.) The trend of worsening performance is particularly evident in the case of the OBE, where instances of level 2 performance begin to appear in year 5 and become more frequent, and in the case of the IBE, where mean performance deteriorates from Level 3 in the first few years to close to Level 4 (“Inadequate”) in the latter years of analysis.

The figure also shows that the existing system does not meet the performance objective specified earlier, that is a 70 percent probability of meeting the AWWA 70% area/70% flow criteria (i.e., Level 3 or better) in a DBE. At first glance, it would seem from Table 3 that any upgrading effort to meet this performance goal that costs over $346,000 would not be cost-effective from the point of view of reducing earthquake-related losses. However, this does not consider the benefits of pipe replacement for reducing maintenance costs in addition to earthquake-related costs.
Table 4 compares baseline results with those of 3 simulated seismic upgrading alternatives from the point of view of total life cycle costs and impact on mean performance levels in the first year of analysis. Link 3 represents the strongest candidate for upgrading a single link in the system. Not only is it one of the two older cast iron pipe links in a liquefaction-prone area, it is on the principal pipeline serving Area B (node 3) which contains the critical industrial facility. Upgrading Link 3 alone costs $200,000, but this cost is shown in Table 4 to be outweighed by the savings afforded in maintenance, repair and user costs. Notice that the savings in expected earthquake damage repair costs ($3,000) are small, but the savings in associated user costs ($160,000) and maintenance costs ($178,000) are substantial. Total life cycle costs are thus reduced from $3.144 million to $3.003 million. While the improvement to service area B’s performance reduces user costs, mean system performance levels in a DBE remain at 3.95. Recall that performance level 4 occurs when flow ratios drop below 33% in any 2 service areas, so that improving Area B alone has little impact on system performance.

An alternative would be to upgrade Link 7 in addition to Link 3, improving service at Area C as well as B. Table 4 shows that this does improve system performance significantly, from 3.95 to 3.20. It also meets the system performance objective. However, it is not the minimum life cycle cost alternative, since total costs are $14,000 higher than with the option of upgrading Link 3 alone. Additional links can be retrofitted to further improve system performance (e.g., upgrading Link 2 as well improves performance to 3.05), but at higher total life cycle cost. Figure 4 shows this performance-cost tradeoff in graphical form. It also demonstrates how imposing performance criteria moves the optimal solution away from the cost-minimizing one.

Table 4. Cost and Performance Effects of Seismic Upgrading Alternatives

<table>
<thead>
<tr>
<th></th>
<th>No Upgrading</th>
<th>Upgrade Link 3 only</th>
<th>Upgrade Links 3&amp;7</th>
<th>Upgrade Links 3,7&amp;2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upgrade cost, $mil.</td>
<td>$0.000</td>
<td>$0.200</td>
<td>$0.700</td>
<td>$1.000</td>
</tr>
<tr>
<td>Maintenance cost, $mil.</td>
<td>$2.798</td>
<td>$2.620</td>
<td>$2.176</td>
<td>$1.909</td>
</tr>
<tr>
<td>Repair cost, $mil.</td>
<td>$0.034</td>
<td>$0.031</td>
<td>$0.027</td>
<td>$0.026</td>
</tr>
<tr>
<td>User cost, $mil.</td>
<td>$0.312</td>
<td>$0.152</td>
<td>$0.114</td>
<td>$0.107</td>
</tr>
<tr>
<td>Total cost, $mil.</td>
<td>$3.144</td>
<td>$3.003</td>
<td>$3.017</td>
<td>$3.042</td>
</tr>
<tr>
<td>Mean System Perf. (DBE, yr.1)</td>
<td>3.95</td>
<td>3.95</td>
<td>3.20</td>
<td>3.05</td>
</tr>
</tbody>
</table>
It should be noted that even for a system as simple as the hypothetical example here, finding the cost-minimizing retrofit alternative may not be a trivial problem. In this case, there are hundreds of possible link upgrade combinations. To determine the user cost reduction for each combination, the hydraulic analysis simulations must be performed to evaluate the impact of the retrofits on flow ratios at each demand node. That is to say, the user cost reduction from upgrading links X and Y is typically greater by some indeterminate amount than the sum of the reductions from upgrading each individually. However, the set of retrofit possibilities to be investigated can be substantially reduced by first strategically evaluating a few alternatives.

The optimization problem can be solved for the current example by first showing that Links 9, 10, and 11 cannot be a part of any cost-minimizing solution. For these links, the maximum maintenance, repair and user cost savings will always be less than the cost of seismic upgrading. Second, Links 3 and 7 must be included in any upgrading scheme if the performance objective is to be met. This can be shown by simulating system performance with and without upgrading these links. Of the remaining 32 retrofit possibilities that meet the conditions noted, most can be eliminated without performing the actual simulation. Since upgrading costs and maintenance and repair cost savings can be readily determined for each link, the question is the amount of user cost savings that can be associated with each alternative. Upper bounds on user cost savings can be placed by noting that the savings associated with upgrading any set of links cannot be exceeded by upgrading any subset of those links. Using this approach, for the hypothetical example given, upgrading Links 3 & 7 can be shown to be the cost-minimizing seismic retrofit option subject to the performance criteria constraint. While such an approach is adequate for a very simple system, to evaluate a more complex system, a more rigorous and efficient optimization mechanism should be developed.

V. Conclusions
This paper has demonstrated how the concept of life cycle cost analysis can be applied to infrastructure systems, particularly water delivery systems, for natural hazard risk management. As has been vividly demonstrated in such disasters as the 1995 Great Hanshin (Kobe) Earthquake, infrastructure system failures can cause substantial user costs in the form of economic disruption, and these costs should be considered in addition to physical repair costs. Furthermore, while seismic upgrading programs such as selective pipe replacement may not be cost-effective from the standpoint of reducing earthquake losses alone, the associated benefits of reduced long-term maintenance costs can be important and should be considered. The life cycle cost framework presented here provides a means for determining how to most cost-effectively attain specified seismic performance objectives for lifeline systems.

Findings from this study indicate a number of areas for further research that will be important in developing applications to more complex systems. First, the data inputs should be improved as far as possible based on experience data. This is particularly critical for the various cost parameters. While it is also important to more accurately quantify the parameters describing physical condition deterioration over time, empirical data may be impossible to obtain and values might at best be inferred based on expert judgment. Similarly, while difficult to quantify, the user cost parameters should also be consistent with observations in previous disasters.

Analytical components of the methodology can also be improved. For example, seismic upgrading options for pipelines can be refined by considering joint type. Damage due to liquefaction can be modeled explicitly rather than approximately through the assumption of poor soil type. User costs can be modeled with much greater sophistication by incorporating actual economic loss models. Sensitivity analysis should be performed to facilitate expert judgment on the credibility of the results, to incorporate uncertainty in the underlying data, and to identify critical parameters for further investigation. As noted earlier, an efficient optimization algorithm is needed to help identify the cost-minimizing solution.

One particularly significant area for further research concerns the identification and operationalization of performance levels and performance criteria. The definitions shown in Table 1 were proposed for demonstration purposes only and many other alternative definitions are possible. For example, system performance can be defined in terms of fire-fighting capacity and water quality, suggesting that other indices such as water pressure be incorporated. The issue of defining performance criteria, that is levels of acceptable performance, presents an especially complex problem that involves societal as well as engineering issues.

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