Economics of Seismic Retrofit of Water Transmission and Distribution Systems

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1 Introduction

This paper examines the economic basis for seismic retrofit of water transmission and distribution systems. An estimate is made as to the size of the "marketplace" for seismic retrofit of water systems in the United States. An economic analysis is then presented for the seismic retrofit of the Hetch Hetchy water system.

2 The Marketplace for Seismic Retrofit of Water Systems

One way to gage the need for seismic retrofit of water systems is to examine the case evidence as to how much has been already spent on such endeavors. In the United States, there are more than 10,000 individual water system operators. Of these, perhaps a few dozen or so have embarked on some sort of system-wide seismic retrofit. This is not to say that the other water utilities have ignored seismic issues: in fact, the vast majority of water system operators follow codes like the UBC 97 for design and construction of new buildings. But the fact of the matter is that much of the water infrastructure currently (year 2003) in place has been designed and constructed either to no seismic standard (as is the case for 99.9%+ of all buried water pipelines and redwood tanks); out-dated seismic standards (as is the case for most pre-1973 steel and concrete tanks); arguably inadequate seismic standards for steel and concrete tanks built post-1972 in high seismic regions; lack of attention to seismic detailing for many types of non-structural items such as anchorage of motor control centers, restraint of emergency generator batteries, use of vibration isolators for diesel generators and air compressors, use of flexible suspended t-bar ceilings over operator work areas, lack of restraint of glassware and equipment in water quality laboratories, etc. About the only type of component that is consistently built to relatively good seismic standards are building structures, likely because the UBC (and similar) codes of the past many years are reasonably good and quite rigorously followed.

On a percentage basis of the value of all installed assets (including buildings, pipelines, tanks, water treatment facilities and wells), perhaps only 10% to 20% of the existing inventory has been built to modern-day concepts of earthquake-resistant and/or earthquake-reliable design. This excludes dams, the vast majority of which are well designed for earthquake loads. The reason dams are reasonably well built for earthquake loads lies in their importance; their obvious potential for large life-safety threat should they fail; and in many cases, careful regulatory oversight.

The remaining inventory of water systems (pipes, tanks, non-structural components, etc.) has little direct-life safety threat should there be failures. For this reason, up to the early 1990s, the remaining inventory has not had much attention with regards to seismic issues.

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Since the early 1990s, a growing number of U.S. and Japanese water utilities have examined their seismic vulnerabilities. These efforts have in part been promulgated by the poor performance of a few water systems in the 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes. Invariably, when utilities consider economic impacts of water outages to their customers, they come to the realization that some type of seismic mitigation is economically warranted. Table 1 lists a few such examples.

Water Utility	Population Served	Capital Cost ($)	Cost Per Person ($)
East Bay Municipal Utility District	1,200,000	$240,000,000	$200
San Diego Water Department	1,200,000	$46,000,000	$40
Los Angeles Dept of Water and Power	3,500,000	$1,000,000,000	$285
Contra Costa Water District	430,000	$120,000,000	$280
Portland, Oregon	800,000		$10 est
Seattle, Washington	1,300,000	>$20,000,000	$20
St. Louis, Missouri		$20,000,000	$30
Memphis Tennessee	800,000	$20,000,000	$25
San Francisco Public Utilities Commission (Hetch Hetchy)	2,400,000	$1,300,000,000	$540
San Diego County Water Authority	2,400,000	$700,000,000	$290

Table 1. Capital Cost for Seismic / Reliability Retrofits – United States

A few notes are made for Table 1. The capital costs shown are not in constant dollars. The data used to develop these costs are based on discussions with each utility or consultants working for each utility. The costs reflect expenditures made through 2003, or planned by the year 2015. For EBMUD, the costs include upgrades for its treated water and raw water systems. For the SFPUC, the costs are only for seismic upgrades for its Hetch Hetchy transmission system. The costs sometimes reflect upgrades made for both *seismic* and *reliability* upgrades. While much of the upgrades can be identified with specific seismic-only upgrades (like anchoring a tank), it is more imprecise to state that the installation of a new pipeline or new reservoir is made only for seismic issues, as the decision might have also been influenced for non-seismic issues like drought, system build out, maintenance or other issues. However, it would be reasonable to say that without the underlying seismic threat, most of these reliability-based projects might not have been implemented.

There is a striking difference in cost per person for difference utilities. For example, in high seismic regions like the San Francisco Bay Area, the cost per person is $200 or higher per person. In contrast, in lower seismic regions like San Diego, Memphis and Seattle, the cost per person is more like $20 to $50 per person. This large difference in cost is not to say that the existing infrastructure in Memphis is better than that in Oakland, but rather that the likelihood of large earthquakes in Memphis is lower than in Oakland or San Francisco.

Table 2 provides the corresponding costs being budgeted by a variety of Japanese utilities. The data in Table 2 is taken from discussion with engineers at each utility, and is converted to US dollars at a rate of about 110 Yen = $1 US.

Water Utility / City	Population Served	Capital Cost ($)	Cost Per Person ($)
Hiroshima	1,140,000		>$300
Tokyo	11,000,000		~$300
Kobe	1,500,000	$1,360,000,000	$900
Yokohama	3,374,000		~>$300
Osaka	2,600,000	$1,000,000,000	$380
Hanshin	2,000,000	$16,000,000	$8
Hachinohe	338,000	$50,000,000	$150

Table 2. Capital Cost for Seismic / Reliability Retrofits – Japan

Table 2 shows that Japanese utilities are spending more on average than US water utilities, with $300 per person (or more) being the norm. The Hanshin water utility is a wholesaler, and the relatively low cost ($8 / person) would be added to the final cost per person for people in Kobe (Kobe City buys water from Hanshin). The typical cost for water for a Japanese resident is reasonably similar to the typical cost for a US resident.

Table 3 provides the projected US-wide "marketplace" for cost-effective seismic retrofit of water systems. The "High Risk" regions includes much of coastal California, parts of Alaska, Hawaii, coastal Oregon and Washington, etc. The "Moderate Risk" regions include areas near the New Madrid fault zone, Charleston, Salt Lake City, etc. The "low risk" regions include New York City, Boston, etc. The "very low risk" regions include most of Texas, Florida, etc.

US – Seismic Region	Population	Cost per Person ($ 2003)	Total Cost
High Risk	40,000,000	$225	$9,000,000,000
Moderate Risk	15,000,000	$30	$450,000,000
Low Risk	68,000,000	$5	$340,000,000
Very Low Risk	157,000,000	$0	$0
Total	280,000,000		$9,790,000,000

Table 3. US Capital Budget for Seismic Retrofit of Water Systems

Through 2001, about $1,500,000,000 had already been budgeted towards various seismic retrofit programs in the US. In 2002, the San Francisco water system (covering the Hetch Hetchy transmission system serving 30 different distribution systems) began a new $3.6 billion dollar program. As of mid-2003, it would appear that about 10% of the cost-effective seismic retrofits within the USA had been completed, with the bulk (90%) yet to be done.

In lesser developed regions of the world, earthquakes impact water systems at least as badly as they have done in the US and Japan. Recent earthquakes in Izmit Turkey (1999), Bhuj India (2001) and Moquegua Peru (2001) have led to widespread and long term (months) disruptions of piped potable water. Post-earthquake investigations of these earthquakes by TCLEE and others have shown that the affected water system owners had done essentially nothing to improve their systems for earthquakes, even after the compelling evidence available from the 1989 Loma Prieta, 1994 Northridge and 1995 Kobe events. Why have water system operators not done anything? Certainly not because they wished to have an earthquake cause several month water outages; but more probably because they a) were not aware of the seismic hazard; b) they knew about the seismic hazard, but had no direction (codes, standards, guidelines) to direct them what to do; or c) they knew about the seismic hazard and they knew about how to mitigate the risk, but they were not economically inclined to do anything about it; perhaps their impression was that "it was not worth the money".

3 Economics of the Seismic Upgrade of the Hetch Hetchy Water System

If one approaches the typical water utility owner, and asks them if "it is worth it to upgrade their water system for earthquakes?", one will most often get one of the following five stages of response:

1. I don't have a problem…
2. I did not know I had a problem…
3. I sense that there might be some type of problem, but I don't know how to quantify it…
4. I am pretty sure I have a problem, so I will take a shotgun approach and fix / improve as many parts of the system as my (regulators / city council / rate payers) are willing to pay for…
5. I know I have a problem, so I will study it and develop a rational and cost effective approach to address it….

In high seismic regions like Coastal California, the author has experience with various water utilities that have provided all of these five stages of response. Some of the larger water utilities serving a million or more people (like the City of San Diego, the Santa Clara Valley Water District, the East Bay Municipal Utility District) have adopted approaches consistent with response 5. Many other water utilities, serving populations from 15,000 people to millions of people have adopted any or all of responses 1, 2, 3 and or 4, with the result that some utilities are spending too little and some are spending too much. One intriguing example is currently taking shape: the seismic and reliability upgrade of the aging SFPUC Hetch Hetchy water system.

The Hetch Hetchy system is a water transmission system delivering water from Yosemite National Park (and a few other local supply sources) to about 2,400,000 people in the San Francisco Bay Area. These 2,400,000 people are served by 30 separate water distribution systems, the largest of which (770,000 people) is the City of San Francisco's own distribution system. Ownership, operation and maintenance of the Hetch Hetchy system is by the San Francisco Public Utilities Commission (SFPUC). The remaining 29 water distribution systems (the so-called "suburban customers") purchase water from the SFPUC, and pay for about 70% of the cost to operate, maintain and upgrade the Hetch Hetchy system. At times, the wishes of the 29 suburban customers do not line up exactly with the wishes of the SFPUC.

Since the late 1990s, the SFPUC has been studying seismic and other reliability aspects of the Hetch Hetchy system. In January 2000, the SFPUC completed their "SFPUC Facilities Reliability Program". This effort simulated the overall SFPUC water system reliability in the event of a major earthquake on the San Andreas, Hayward, Calaveras or Great Valley faults. The effort reportedly used the "most current understanding of effects of infrastructure from ground shaking, fault crossing and liquefaction". The analyses resulted in a recommended program of seismic improvements to increase overall SFPUC system reliability. The overall cost of this program was estimated at $3.5 Billion, of which $1.3 Billion was for seismic improvements, and the remainder for reliability improvements. These amounts include no funds to make improvements in the 29 suburban distribution systems.

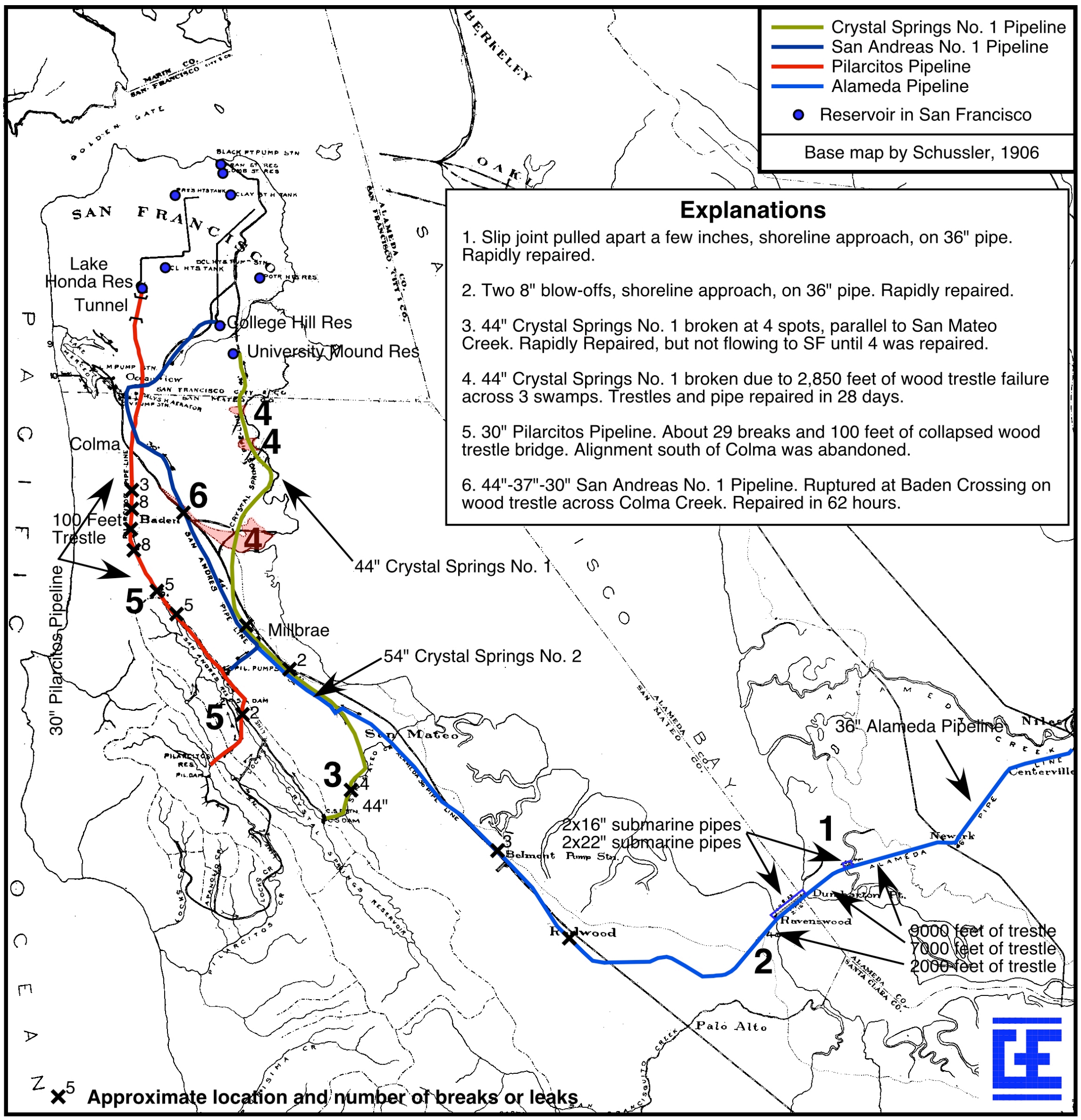

Figure 1. Damage to the SFPUC (Spring Valley Water Company) Transmission System, 1906

Figure 1 shows a map of the SFPUC transmission system as it existed in 1906 and the damage it suffered in the 1906 Great San Francisco earthquake. The modern (year 2003) SFPUC transmission system has about 3 times as many pipelines, many of which follow similar alignments as the pipelines did in 1906, except that newer pipes bypass the marshy area marked by the number "4" in Figure 1.

While it remains unclear as of 2003 as to exactly how much the 29 suburban agencies will pay for this program, it is likely that the final cost of the Hetch Hetchy system reliability upgrades will roughly triple the cost to purchase SFPUC water.

4 What About the Suburban Customers?

With large potential rate increases facing the suburban customers of the SFPUC, the level of awareness about seismic issues has risen from "about" stages 1 or 2, and most are now thinking about responses at stages 4 or 5. A series of seismic vulnerability analyses have been performed for many of the suburban customers.

Item	Amount	Note
Average Day Demand	286 MGD	81% of total system demand
Number of Pump Stations	151	
Number of Storage Tanks	192	
Miles of Distribution System Pipelines	3,713	Mostly 4" to 27" pipe
Wells	85	
Treatment Plants	6	
Emergency Generators	63	
Pipe Repairs, San Andreas M 7.9 Earthquake	2,400 to 5,000	Lower value is more likely
Pipe Repairs, Hayward M 7.1 Earthquake	1,400 to 3,600	Lower value is more likely
Seismic Improvement Program	$25 to $44 million	

Table 4. Statistics of 18 Suburban Customer Water Systems

The 18 suburban customers that have had seismic vulnerability analyses performed (Hayward, Alameda County Water District, City of Santa Clara, Mountain View, Purissima Hills, Palo Alto, Stanford University, Bear Gulch, Redwood City, San Carlos, San Mateo, Foster City, Coastside County, Mid-Peninsula, Burlingame, South San Francisco, Brisbane, Daly City) represent about 76% of the total suburban customer demand; or in conjunction with the City of San Francisco, about 81% of total Hetch Hetchy system demand. Table 4 provides some overall statistics for these 18 suburban customers.

The modern Hetch Hetchy water system has about 220 miles of large diameter (mostly 60" to 96" diameter) pipelines within the greater San Francisco Bay Area. In consideration of faulting, liquefaction, landslide and ground shaking, these pipes are expected to suffer between 16 and 23 repairs following Hayward M 7.1 and San Andreas M 7.9 earthquakes, respectively. The bulk of these repairs will likely manifest themselves as leaks at air valves or blow offs, but a few full breaks are likely at fault crossings, creek crossings or at unexpected locations. There is even a chance that a major tunnel might collapse. With available in-house repair crews, the SFPUC might be able to patch up the major breaks in 4 to 12 days, and repair all leaks within 1 to 2 months. If the unlikely but not impossible event that a major tunnel should collapse, repairs of the tunnel could last months, in the meantime the water supplies might have to be restricted to no more than about 80% of maximum winter time demands.

Given these scenarios, the following seismic improvement have been proposed:

- $25 to $44 million of seismic improvements within the 18 suburban customer distribution systems.
- $1.3 to $3.5 billion of seismic and other reliability improvements within the Hetch Hetchy transmission system.

As of mid-2003, there remains much work to coordinate the overall transmission / distribution seismic upgrade programs. For example, should a small suburban customer invest $800,000 to construct a well, thereby providing an alternate source of water should all Hetch Hetchy water be lost for days to weeks after a major earthquake? And if that small suburban customer builds that well, should it also accept the allocated cost to improve the major water pipeline transmission system? What might be most cost effective for that one suburban customer might not be the most cost-effective for other suburban customers, or for the SFPUC as a whole, and this brings up difficult political and policy issues.

Item	EBMUD	SFPUC + 18 Suburban Customers
Miles of Transmission Pipelines	200	220
Miles of Distribution Pipelines	3,900	3,700
Tunnels	16	20
Treatment Plants	6	8
Storage Tanks	175	192
Pump Stations	125	151
Small Pipes that cross major active faults (≤18" diameter)	178	66
Large Pipes that cross major active faults (≥ 20" diameter)	27	11
Tunnels that cross major active faults	2	0
Pipe Repairs, Loma Prieta M 7.1	135	< 400
Pipe Repairs, San Andreas M 7.9	< 1,000	2,400 to 5,000
Pipe Repairs, Hayward M 7.1	3,300 to 5,000	1,400 to 3,600
Seismic Upgrade, Transmission System	$140 million	$1,300 million
Seismic Upgrade, Distribution System	$100 million	$25 to $44 million
Seismic Improvements, Total	$240 million	$1,325 to $1,340 mil.
Ratio, Distribution to Total	42%	2% to 4%
Population served	1,200,000	2,400,000
Cost per person	$200	$555

Table 5. EBMUD and SFPUC / Suburban Customer Cost Allocation

To provide some insight to these issues, one can examine the allocation of seismic upgrade cost made by EBMUD in their $240,000,000 seismic upgrade program. EBMUD is a utility that owns and operates both a raw water transmission as well as a large potable water distribution system. For EBMUD's case, if one sums up all costs associated with raw and treated water pipelines of 36" diameter and larger (cumulatively, the "transmission system"), EBMUD has spent about $140,000,000 on transmission upgrades. The remaining $100,000,000 was allocated to upgrades of smaller diameter pipelines (generally 12" to 30" diameter), water treatment plants, pump stations, storage tanks and emergency response. Table 5 highlights the differences in upgrade costs between EBMUD (actual) and SFPUC / Suburban customers (projected).

The age of infrastructure in the EBMUD and SFPUC transmission systems is quite similar. The original EBMUD transmission pipelines and tunnels were put into service in 1929 (Mokelumne 1, Claremont Tunnel); the original Hetch Hetchy pipelines and tunnels were put into service in 1923 to 1933 (BDPL 1 and 2, Coast Range Tunnel). EBMUD's first major transmission pipeline system upgrade was put in service in ~1948 (Mokelumne 2); similar for Hetch Hetchy (BDPL 3). EBMUD's most recent major transmission pipeline system upgrade was put in service in ~1965 (Mokelumne 3); similar for Hetch Hetchy (BDPL 4).

5 Economic Impacts to Suburban Customers

A series of seismic vulnerability analyses were performed for 18 water distribution systems that are served by the Hetch Hetchy transmission system. These 18 systems have a combined average day demand of 228 MGD, and serve a population (year 2020) of 1,419,000 people. Allowing for 20 to 30 day outages from the SFPUC transmission system (probably upper bound, more likely 4 to 12 days), and a variable amount of impacts to the local distribution systems (pipe repairs, damaged tanks, failed wells, power outages, etc.), and using the Fire Ignition and Spread models by Eidinger (1996), the following statistics (medians only) are developed:

Item	San Andreas M 7.9	Hayward M 7.1
Economic Losses, Year $2003	$1.4 to $1.6 billion	$250 to $610 million
Fire Ignitions	95	73
Fire Losses, Calm Winds	$85 to $142 million	$65 to $110 million
Fire Losses, Light Winds	$200 to $342 million	$153 to $262 million
Fire Losses, High Winds	$1.1 to $1.4 billion	$0.9 to $1.1 billion

Table 6. Impacts to 18 Distribution Systems in Scenario Earthquakes (As Is System)

Item	San Andreas M 7.9	Hayward M 7.1
Economic Losses	$93 to $333 million	$127 to $535 million
Fire Losses, Calm Winds	$14 to $57 million	$11 to $44 million
Fire Losses, Light Winds	$85 to $114 million	$66 to $88 million
Fire Losses, High Winds	$1.0 to $1.1 billion	$0.8 to $0.9 billion

Table 7. Impacts to 18 Distribution Systems in Scenario Earthquakes (Upgraded System)

The "upgraded system" evaluation is performed for the same 18 distribution systems, but this time with the assumption that seismic upgrades are in place to reliably assure that no more than a 24 hour outage of delivery of maximum winter time demand rate water from the Hetch Hetchy transmission system to each distribution system.

By comparing the difference in losses (economic and fire) from Tables 6 and 7, we can estimate the net benefit (scenario earthquake basis) of the retrofit program. Using the midpoint values, and assuming the light wind scenario, the net reduction in losses (ie, the benefit) is:

Item	San Andreas M 7.9	Hayward M 7.1
Benefit, Economic Impacts	$1,250 million	$99 million
Benefit, Fire Impacts	$172 million	$131 million
Benefit, Other Impacts	$200 million	$40 million
Total Benefit (Scenario Based)	$1,622 million	$270 million

Table 8. Net Benefits of Seismic Upgrade, Scenario Based

Allowing that there is about a 1% chance of occurrence of either of these two or similar scenario earthquakes (San Andreas M 6.8 to 7.9 event that includes the Peninsula fault segment, Hayward M 6.8 to 7.3 event that includes the southern Hayward fault segment), and allowing for other earthquakes on other faults and for smaller earthquakes, and assuming a 5.5% discount rate, and using the benefit cost model for water systems outlined in (Eidinger and Avila, 1999), the net present value of the benefits of seismic upgrades are calculated as follows (all monetary values in millions, year $2003):

- San Andreas M 6.8 – M 7.9: $1,622. Annual chance: 0.01. Annual benefit: $16.22
- Hayward M 6.8 – M 7.3: $270. Annual chance: 0.01. Annual benefit: $2.7
- Calaveras, Rodgers Creek, Great Valley, background and smaller earthquakes: Cumulative annual benefit = $9.7
- Total annual benefit over all faults, all magnitudes = $28.6
- Net present value of benefits, 5.5% discount rate, 100 year project life = $28.6 x 18.1 (NPV factor) = $518

In other words, the rate payers of the 18 distribution systems should be willing to pay, in year 2003 dollars, up to about $518,000,000 to seismically retrofit the Hetch Hetchy water system to the point where it can reliably restore water to each system within 24 hours after any earthquake, at maximum winter demand rate or higher.

6 Conclusions and Observations

The estimated size of the marketplace for cost effective seismic upgrade of water systems in the United States is about $10 Billion (year 2003 dollars). Perhaps 20% of this has been spent through mid-2003.

A comparison is made between the (almost completed) EBMUD seismic upgrade program and the (recently started) SFPUC seismic upgrade program. While there are a number of similarities between the age and quantity of infrastructure between of the two sets of water systems, the cost of the programs is quite different, as well as the ratio of cost between distribution and transmission upgrades.

By performing seismic vulnerability analyses for 18 suburban distribution systems served by the SFPUC Hetch Hetchy system, and then performing economic analyses as to the value of seismic upgrades, this paper shows that these suburban customers should be willing to pay up to about $518,000,000 to achieve a no-more than one-day outage of the Hetch Hetchy transmission system after any earthquake. Retrofits and improvements beyond this cost could be justified for non-seismic reliability issues.

7 Units and Abbreviations

All monetary values are in year 2003 U.S. dollars, except as noted.

BDPL = Bay Division Pipeline

EBMUD = East Bay Municipal Utility District

Inches (") = 25.4 millimeters

M = moment magnitude

Miles = 1.609 kilometers

MGD = Million Gallons per Day (US liquid measure). 1 MGD = 43.8 liters per second

NPV = Net Present Value

SFPUC = San Francisco Public Utilities Commission

TCLEE = Technical Council on Lifeline Earthquake Engineering

UBC = Uniform Building Code

8 References

Eidinger, J., and Avila, E., Eds., Guidelines for the Seismic Upgrade of Water Transmission Facilities, ASCE, TCLEE Monograph No. 15, January 1999.

Eidinger, J., Lifeline Considerations and Fire Potential, *in* Seismic Safety Manual, D. Eagling editor, Lawrence Livermore National Laboratory, September 1996.