REPLACING SEISMICALLY-WEAK AND AGING WATER PIPES

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ABSTRACT

Pipe replacement due to seismic issues and pipe aging is a major cost for water utilities. Current American and Japanese approaches to water pipe replacement are reviewed. A case study of pipe replacement in Pasadena, California is examined. A recommend approach for pipe replacement is suggested.

Introduction

The United States Environmental Protection Agency has identified that US water utilities need to invest $500 billion to replace aging water pipelines. ASCE consistently gives water utilities a "D- or perhaps a C-" score card with respect to the state of their aging infrastructure. In California, as in other parts of the world, many water agencies are grappling with seismic issues and the weakness of buried pipelines to the effects of liquefaction, landslide, fault offset and ground shaking.

This paper examines whether (or not) it is cost effective to replace aging water pipes to better withstand earthquakes. A recommended pipe replacement strategy is provided.

Costs to Install and Replace Pipes

The oldest water pipelines now installed in the USA date back to the late 19th century. The bulk of the current inventory of pipelines were installed between 1910 and 1930 (perhaps 15% of current inventory) and between 1950 and 1980 (perhaps 70% of current inventory). The prime reason to install these pipes was to provide potable water service to residential, commercial and industrial customers, as these facilities were originally built. In many cases, the water pipes were installed in "virgin" streets, meaning that the pipe was installed as the subdivision was originally built. In year 2010 US dollars, the common cost to install these pipes was about $422,000 per mile (or about $10 per inch-foot = $422,000 / 5280 feet / 8 inches). Commonly, 1 mile of pipe in urban areas serves about 325 (±100) people. Therefore, the capital cost for initial installation of pipe was about $1,300 per capita (= $422,000 / 325 people). These costs should be considered "typical", and would vary considerably between regions of the country, different cities, and within different areas within a given city.

Today, the cost to replace an old 6-inch diameter water pipe with a new 8-inch diameter water pipe (no special seismic design) in an existing urban environment (Oakland

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California) is about $1,500,000 per mile using cut-and-cover methods (about $36 per inch-foot). The reason for this nearly 4-fold increase in cost is that the replacement pipe effort must be done in congested streets (adds a lot of cost), much planning needs to be done (more detailed drawings are created today than originally), the new pipe is commonly larger diameter (reflecting an increased fire flow requirement over the years, increased peak hour demand, etc.), limiting water outages to existing customers, increased safety regulations, the need to properly dispose of any contaminated soils, more costly work rules, and other factors.

Different American and Japanese Approaches

Soon after the 1989 Loma Prieta earthquake, EBMUD (water utility serving Oakland and 21 other cities and communities in the eastern portion of the San Francisco Bay Area) began a comprehensive seismic upgrade program for its water transmission and distribution systems. By 2010, EBMUD had spent well over $300,000,000 to address seismic issues alone. EBMUD has about 4,000 miles of transmission and distribution water pipes, serving 1,300,000 people. Even though EBMUD recognized that it might suffer between 3,000 to 5,000 broken and leaking pipes in a large earthquake on the Hayward fault (annual chance about 1%), not a single penny of this $300,000,000 was devoted to replacement of distribution water pipes. Instead, EBMUD spent this money in the following areas (approximate percentages): seismic upgrade of tanks and potable water reservoirs (20%), seismic upgrade of pump stations and water treatment plants (5%), construction of a new transmission pipeline to provide redundancy for other pipes expected to fail in earthquakes (12%), upgrade of a transmission tunnel that crosses a fault (12%), installing emergency bypasses for non-redundant "backbone" pipes in liquefaction, landslide and fault offset zones (commonly 12" to 30" diameter) (10%), upgrading a large dam (10%), installing valves in transmission pipes (3%), upgrading occupied buildings (5%), procurement of above ground hoses (8" to 12" diameter) (1%), purchase of additional portable pumps (1%), emergency response planning and supplies (1%), and programmatic costs (engineering, project management, etc.).

Even with all this expenditure, almost none of it went towards replacement of older / seismically vulnerable pipes with new pipes. Therefore, EBMUD will still need to deal with repairs to potentially thousands of damaged pipes after a large future earthquake.

Since the 1995 Kobe earthquake, the JWWA (Japanese Water Works Association) issued updated seismic guidelines and pipe replacement guidelines. These guidelines included provisions (simplified) that all water pipes need to be replaced once they have reached a 40-year lifetime. Since the issuance of these guidelines, several large Japanese water utilities have tackled this issue, refining these guidelines to be more like: replace older seismically vulnerable but less important pipes in 65 years, replace older seismically vulnerable and more important pipes in 40 years, and replace them with newer "seismically-designed" water pipes. In Japan, "seismically-designed" water pipes include ductile iron pipes with limited slip/rotation "chained" joints, or welded steel pipes. The Ductile Iron pipe manufacturers in Japan seem to be enjoying a re-birth of substantial water pipeline construction!

JWWA – AWWARF Seismic Workshops

After the disastrous 1995 Kobe earthquake (disastrous = major water outages of the water systems in cities of Kobe, Ashiya, and surrounding communities), coupled with the 1989 Loma Prieta and 1994 Northridge earthquakes, several of the affected water utilities, along with national water associations, JWWA and the American Water Works Association research Foundation (AWWARF, now WRF) decided to hold bi-annual meetings. The most recent such meeting was held in Taipei, Taiwan in 2009, with prior meetings held in Tokyo, Kobe, Los Angeles, and Oakland (2 times). Participants at these meetings have included about 10 Japanese, 10 American, 2 Taiwanese, 1 English water utility as well as leading water-system-seismic researchers / practitioners from Japan, Taiwan, United States and Italy. Each workshop has typically included presentations and technical papers on how each utility is addressing seismic issues.

One of the most stark contrasts in technical approaches between Japan and the USA has been that Japanese utilities are spending large amounts of money to replace seismically-weak pipes (commonly on the order of $1,000,000,000 per large city), while American utilities are spending nearly nothing to replace seismically-weak pipes. Lively discussions between the workshop participants about these differing approaches have yielded the following key points:

- US utilities would like to replace seismically-weak pipes, but the great cost involved precludes such implementation.

- Japanese utilities are following "JWWA" guidelines, and these require installation of seismically-designed water pipes.

- Japanese utility engineers develop an optimized pipe replacement strategy, at a specific cost. US utility engineers query the Japanese utility engineers, to ask them how they get this cost approved. The common Japanese response is: "the utility sets the rates, and the customers are willing to pay". US utility engineers seem amazed, and don't believe this approach would "pass muster" within their rate-setting environment.

- US utilities are keen to consider "benefit-cost" approaches to replacement of pipe. Only if the Benefit-Cost-Ratio (BCR) is greater than 1 (sometimes 2, 3 or 4), are US water utility Boards of Directors willing to pass on the extra cost to customers.

- At least though 2009, Japanese water utilities do not apply BCR ratios in a quantified manner to justify rate increases to cover the cost for replacement pipes.

- Existing water pipelines in many Japanese cities include many "skinny" distribution pipes, with substantial percentages of the pipe inventory in the 1-inch to 4-inch diameter range. Many of these use seismically-weak materials. Post-earthquake fire threat is a major concern in Japan, and some utilities rely on small (2,000 gallon to 10,000 gallon) cisterns in city streets to supplement the low fire flows (pressures and flow rates) available by skinny pipes. Just one US water utility (City of San Francisco) still uses water cisterns. The usefulness of these cisterns, in actual post-earthquake events, remains "marginal – skeptical" (they were of not much use in the 1995 Kobe earthquake).

- Unlike Japan, in the USA there is no equivalent AWWA guideline that mandates replacement of older pipes on any specific aging schedule. Other code-setting agencies in the USA (such as UBC, IBC, NFPA, etc.) do not require water pipes to be installed with "seismic-details", even in the riskiest seismic areas (liquefaction, landslide or fault crossing locations).

- ALA has issued a guideline on the seismic design of water pipes (2005); this guideline is non-mandatory. This guideline provides simple approaches (put any kind of pipe in the ground for the lowest cost in lower-risk areas, without any seismic design) to complex (critical non-redundant transmission pipes must be designed to rigorous seismic criteria). ALA allows that each utility may adjust the provisions based on "benefit-cost" considerations, so that additional costs would be warranted if serving high-economic value areas such as Silicon Valley, but zero-incremental costs would be warranted if serving semi-rural residential areas where the incremental economic benefit of seismic-resistant pipes is too small.

- In most areas of Japan, the annual chance of sustaining a large earthquake is perhaps 2 to 4 times higher than most high seismic hazard areas in California. All other factors being equal, this means that there is more benefit for pipe replacement to be gained in a large Japanese city (say Osaka) than in a large US city (say Los Angeles).

USA Asset Management

Over the past decade or so, the concept of "Asset Management" has gained some traction at water utilities in the USA. These concepts are described in AWWA (2006) and AWWARF-EPA (2005). Neither of these documents formally addresses seismic issues as one of the factors to be addressed in pipe replacement. However, these documents and ongoing industry practices do provide the following key points about pipeline replacement.

- Pipe aging is a "wear out" issue. Good ongoing maintenance (corrosion control practices) can extend the life of water pipes.

- The historical pattern of pipe installation in the USA was limited between 1880 and 1910, then low-to-moderate form 1910 to 1945, then major from 1950 to

1980, then moderate from 1980 to 2005.

- Over the past 25 years, the common major US water utility has been replacing existing pipes at a rate of about 0.1% to 0.3% per year. This translates to about a 300 to 1,000 year replacement cycle. For example, EBMUD replaces about 5 miles of pipe per year, out of its 4,000 mile pipe inventory. The City of San Diego Water Department (SDWD, also with about 4,000 miles of pipe) has a similar replacement rate.

- Replacement pipes are commonly non-seismic pipes. For example, it would be common to replace a 6" leaking 1920-vintage cast iron pipe with push-on caulked joints, with a 2010-vintage 8" PVC or Ductile Iron pipe with push-on rubber joints.

- If one assumes that there is truly a "100-year" lifetime for pipes, then most US water utilities are facing a HUGE increase in pipe replacement requirements over the next decade or so. For a moderately large utility such as EBMUD, annual replacement costs will increase from about $7.5 million ($6 per capita) to perhaps $75 million ($60 per capita). In other words, the monthly water bill for a family of four will have to increase by about $17 per month. This represents a substantial rate increase, and might be politically unacceptable to publically-elected Boards of Directors or City Councils.

- Some policy documents are saying that the pipe aging issue is a pending "CRISIS" or "CATASPROPHE". ASCE issues annual proclamations that the nation's infrastructure is in gross disrepair, and gives scopes like "C-" and "D-" for water and wastewater buried pipe systems. Perhaps these are "scare" tactics? or, are these economically sound observations?

Case Study

Given the combined issues of seismic vulnerability, fire threat and pipe aging, the question is whether or not to start an aggressive pipe replacement program; and if so, how much money should be spent, how much rates need to be increased, and, in seismic areas, what kind of pipe should be used for replacement?

Lest we think that this issue has never been tackled before, it is illustrative to examine prior pipe replacement programs in the USA. The case of the water system in the City of Pasadena is presented. As of 2004, there were 509 miles of water pipe in the Pasadena water system. Figure 1 shows the miles of pipe installed in the City of Pasadena water system. Nine types of pipes are used in the Pasadena water system. The oldest pipes installed date back to 1887, and the newest 2004. Figure 1 shows that the bulk of the water pipes in Pasadena were Cast Iron (79% of total inventory); Ductile Iron has been the most common type of pipe installed since about 1983 (11%). Unlike many other cities, Pasadena never installed much Asbestos Cement or PVC pipe.

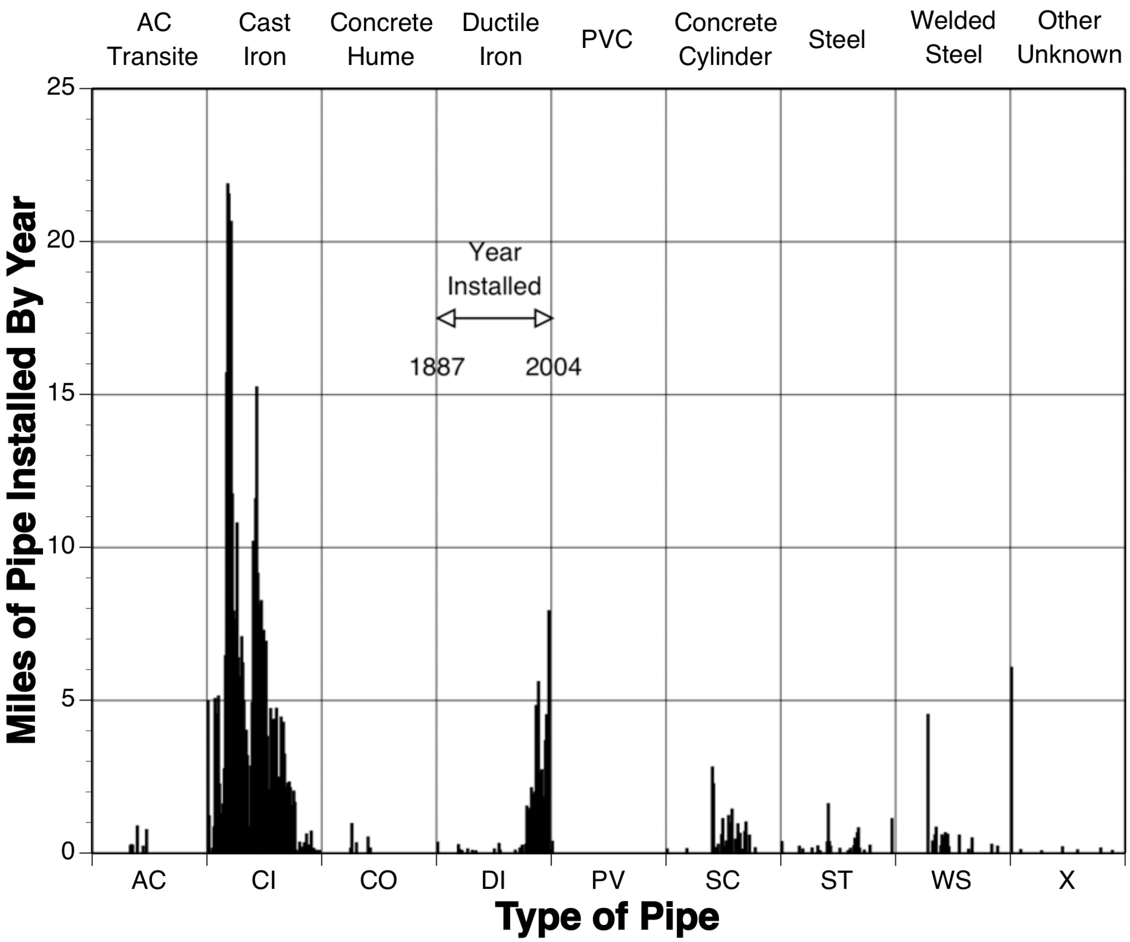

Figure 1. Pipes Installed, by Type and by Year

Pasadena is located just north of Los Angeles, in one of the most seismically active locations in the USA. Pasadena's service area boundaries coincide (roughly) with three active faults (Sierra Madre to the north, Raymond to the south, and Eagle Rock – Verdugo to the southwest). At least 20 other active regional faults threaten Pasadena, including the San Andreas, and a host of blind thrusts. The common probabilistic design-level earthquake ground motions in Pasadena (firm soil sites) is about PGA = 0.55g (475 year), 0.85g (975 year) or 1.10g (2,475 year).

The modern Pasadena water system was formed through the purchase of several water systems. Beginning in 1912 when the Pasadena bought those systems, it inherited all the in-place infrastructure, including water pipelines. As early as 1913, higher pressure in the old pipelines was causing a number of burst thin-walled riveted steel pipes, and the water department began a pipe replacement program.

In 1915, the water system included 188 miles of pipe, of which 117 miles (62%) were riveted steel pipe and 59 miles (31%) were screwed steel pipe. Much of the riveted and screwed steel pipe was thin walled. At that time, none of this pipe would have had good corrosion protection (no sacrificial anodes), and pin holes through the original coating would have been common, leading to pin-hole leaks.

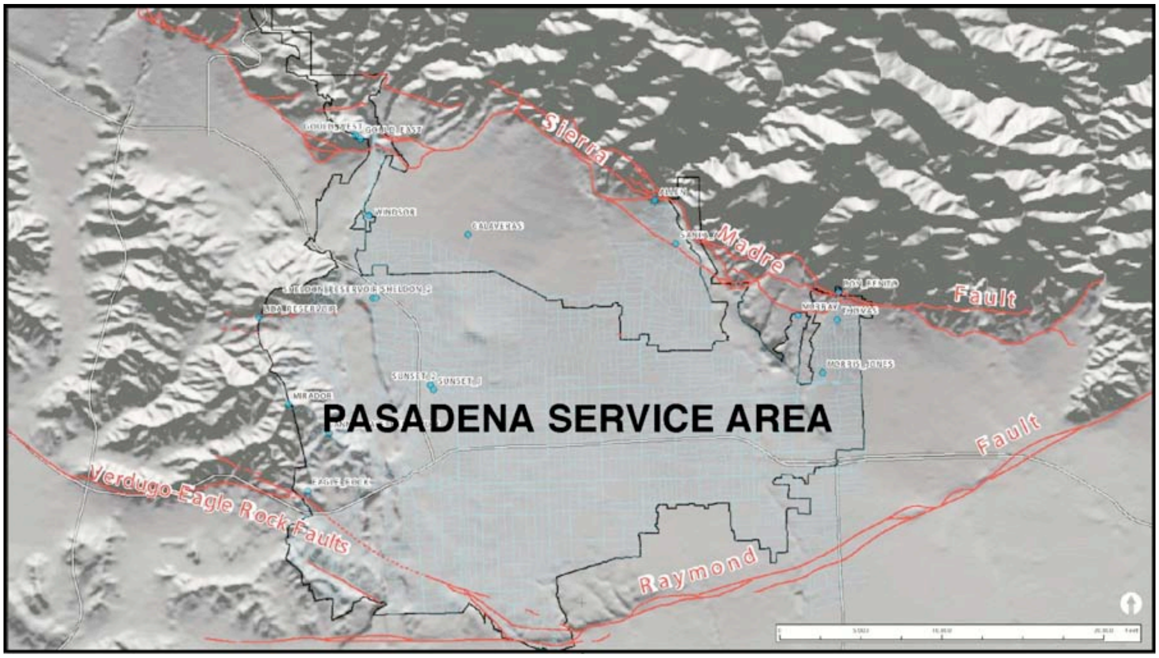

Figure 2. City of Pasadena Water System and Local Active Faults (red lines)

With the purchase of several water systems, the Pasadena water department had to also merge the purchased water systems with its existing pressure zones, requiring that some areas of former low pressure were re-zoned into high pressure zones. The increase in system pressure led to more pipe leaks.

With these factors in mind, the Pasadena water system instituted in 1916 a pipe replacement program, where the thin walled riveted pipe and screwed steel pipe were replaced with heavier wall, higher pressure-rated cast iron pipe. About 6 miles of older pipe were replaced with newer cast iron pipe in 1916. By 1917, thin walled riveted steel pipe was reduced to 51% of all pipe. In 1927, with the construction of a new reservoir, system pressures were increased by 24 psi in one of the pressure zones, leading to further burst pipes and the need to continue replacement of thin-walled pipe with heavier cast iron pipe. With the ongoing pipe replacement program, the 1,080 repaired leaks in 1925 had been reduced to 509 in 1927. By 1951, the bulk of the old thin-walled riveted steel pipe had been replaced and there were far fewer leaks in the system.

To summarize, the pipeline replacement program in Pasadena, between 1916 and 1951 (35 years total), successfully replaced thin-walled pipe that leaked a lot, with "then-state-of-the-art" heavy wall cast iron pipe. Essentially no pipes were replaced during the war (1941-1945), so de-facto the replacement schedule was 30 years (3.3% replacement rate per year). This historic replacement rate is about 10 to 30 times *higher* than the current replacement rate by EBMUD or SDWD.

Pasadena's current inventory of pipe includes the following seismic hazards:

- 31 pipes crossing the Sierra Madre, Raymond or Verdugo-Eagle Rock faults
- 20.5 miles of pipe in moderate susceptible liquefaction zones

- 99.2 miles of pipe in low susceptible liquefaction zones
- 0.3 miles of pipe in very high susceptible landslide zones
- 36.7 miles of pipe in high susceptible landslide zones
- 13.3 miles of pipe in moderate susceptible landslide zones
- 486 miles of pipe in firm soil units

While pipe leaks do occur sporadically in Pasadena, and any pipe leak is of concern, a "larger" concern to water utility management is that a cast iron pipe should not have a major blow out on Colorado Boulevard during the annual January 1 Rose Bowl Parade. While seemingly funny, this concern can be re-stated that a pipe leak / blowout that results in large economic consequences is of much more concern than a pipe leak / blowout that results in minor inconvenience. In other words, benefits of pipe replacement (benefits = net present value of the annualized reduction in losses, *including* economic losses to the served community) should outweigh the initial capital cost.

To develop annualized benefits from earthquakes, one needs to develop system restoration curves of the water system for the various possible earthquakes. The methods to perform such seismic vulnerability analyses include pipeline fragility, facility fragility, power outages, consideration of the seismic hazards (ground shaking, liquefaction, landslide, fault offset), system hydraulics, and post-earthquake response. The results of such two analyses for Pasadena are shown in Figure 3 (Sierra Madre M 7.2 event) and Figure 4 (San Andreas M 7.9 event). These plots show that the "dreaded" San Andreas M 7.9 (popularized recently by the Great Shakeout) is merely a "blip" in Pasadena as compared to the local Sierra Madre M 7.2 earthquake.

The gross economic losses to the community can be quantified as the area above the black curve (measured in customer-days lost) times the economic value of lost water (considering reduction in economic activity and losses due to fires). The net benefits are the *reduction* in such losses should Pasadena implement a pipeline replacement program with new seismic-resistant pipes.

Given these findings, it was found that a pipe replacement program *for seismic issues alone* could not be economically justified for the City Pasadena. Primary reasons include: most of Pasadena's pipelines are located in good soils (no significant liquefaction, landslide, or fault offset threats). So, even though Pasadena will be exposed to high levels of ground shaking, the amount of pipeline damage (up to 140 repairs or so in a large local event, 20-50 repairs in a large distance event) is not so severe as to warrant (on its own) pipe replacement. Instead, for Pasadena, the more cost-effective strategy is to get local wells working within 24 hours after a major earthquake; improve reservoirs and non-structural equipment such that local supplies and pump stations can operate post-event; rapidly respond and repair leaking pipes; and to work with its wholesaler agency (MWD) to assure that MWD can restore at least some water to Pasadena within 3 to 7 days after a Sierra Madre M 7+ event.

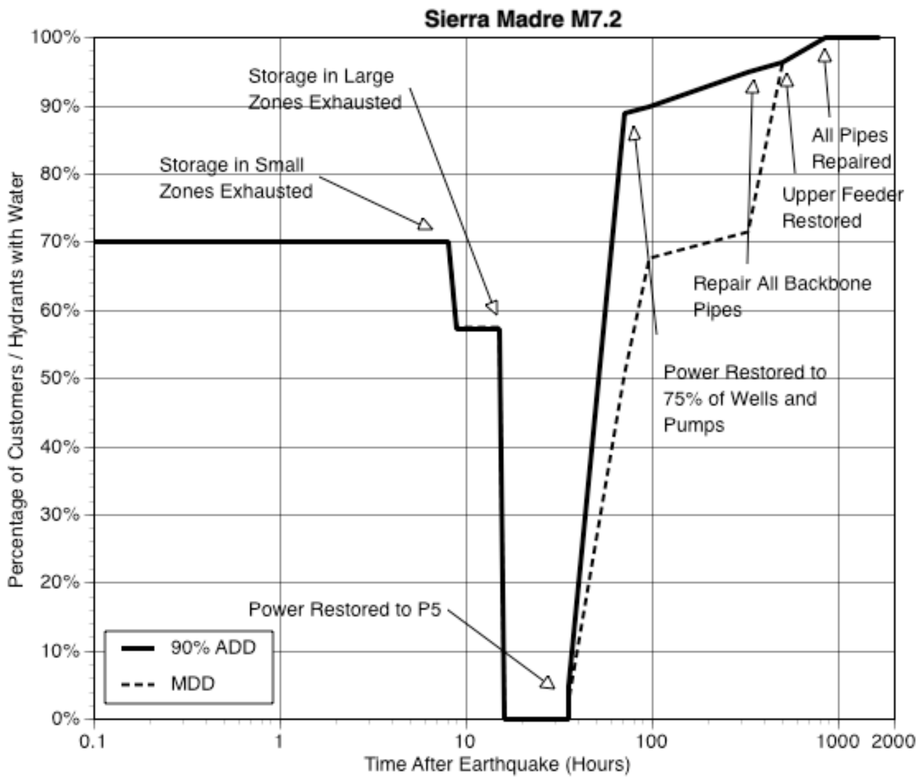

Figure 3. Restoration of Customer Service, Sierra Madre M 7.2 Scenario

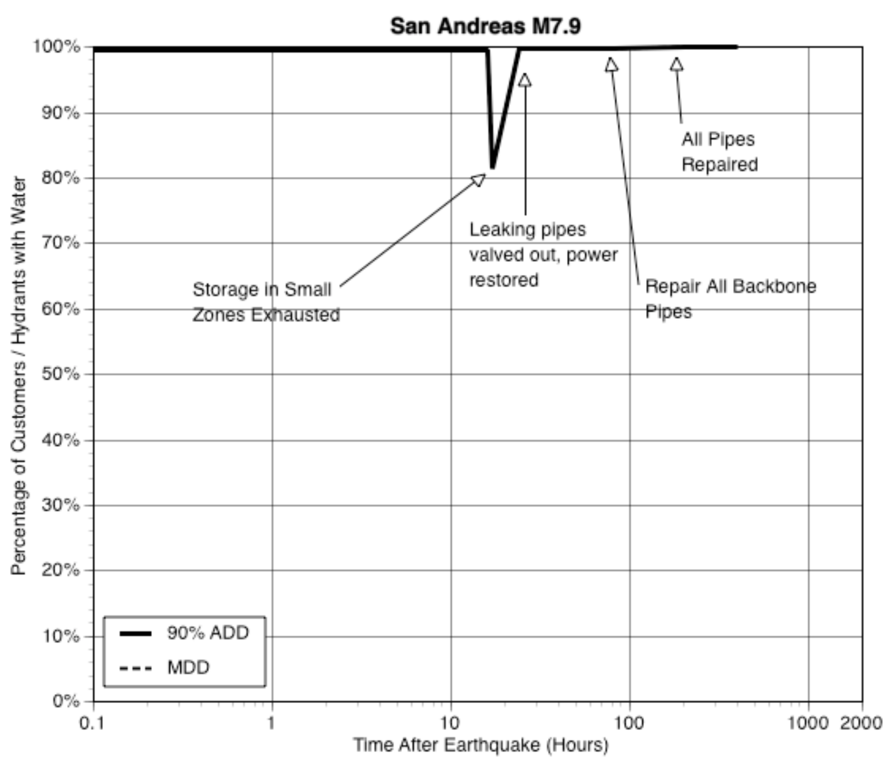

Figure 4. Restoration of Customer Service, San Andreas M 7.9 Scenario

Recommendations

For cities like Pasadena, the long term (ninety years from 2010 to 2100) pipe replacement strategy should look something like the following:

- Replacement pipes in areas zones with moderate to high or very high liquefaction / landslide threat, or traverse active faults, should be seismically designed per ALA 2005. This is true in high seismic risk California (San Francisco, Los Angeles), Kodiak (Alaska), La Malbaie (Quebec) or more moderate seismic risk areas like San Diego, Memphis, Salt Lake City, Portland, Seattle, Vancouver (British Columbia). The decision of when to replace should be based on recent leak history, not on seismic risk alone. In extremely high seismic hazard areas (Eureka California, many areas of Japan), the decision of when to replace pipe might be justified on seismic issues alone.

- Pipes with a known leak history with more than 2 (or 3) leaks within the past 5 years should be high priority for early replacement (within the next ten years). This reflects a variety of benefit cost analyses, and a "willingness to pay" concept. There appears to be a fairly high correlation of the locations of on-going leaking pipes and the locations of high seismic pipeline vulnerability.

- Pipes without a recent leak history should be "left in place" without a specific schedule for replacement. Only in extremely high seismic risk areas, or for critical non-redundant pipes, should pipe replacement be done primarily for seismic reasons.

- Pipes that require replacement due to inadequate fire flows, tuberculation, taste or odor, high leak rate, or other reasons, should be replaced with suitable pipe materials per ALA 2005 or similar seismic guidelines. In a nutshell, if the pipe to be replaced is not exposed to ground failures, then "push on joint" pipes (lower cost) are acceptable, while important pipes exposed to liquefaction should have "restrained" or "chained" joints, while important pipes subject to fault offset should be designed to accommodate the fault offset. For pipes in landslide zones, avoidance is the primary solution (zone the area as not fit for permanent or important facilities); but for existing landslide zones the solution is generally "buyer beware" and the water utility should not have to design to accommodate landslide other than to prescribe restrained joints; and customers in landslide zones must accept the higher risk for damage to water pipes and relatively poor post-earthquake performance. All new pipes should be designed with suitable corrosion protection. The seismic performance of aged (over 40-years) thin-walled ductile iron pipe, with or without "external baggies", located in corrosive environments, is currently unknown.

- Types of pipes that are scheduled for replacement, (say Cast Iron installed between 1930 to 1940) due to ongoing high leak rate, should not be considered uniformly weak elsewhere in the system. Local corrosion cells or weak soils or locally high pressure, or local installation practices, may have much more influence on pipe vulnerability and leakage than the type and age of pipe in general.

- Any long term replacement program should factor in yearly-updated leak data.

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