Seismic Upgrade of Pipes Across the Hayward Fault

by
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ABSTRACT

This paper provides the status of all water pipelines crossing the Hayward fault, and a few other utilities such as sewers, water and transit tunnels, and high voltage power transmission lines. These utilities are owned by EBMUD (water), City of Hayward Water Department, Alameda County Water District, San Francisco Public Utilities Commission, Castro Valley Sanitary District, Bay Area Rapid Transit District, and Pacific Gas and Electric.

For the period between 1990 and 2008, costs for seismic retrofit of existing pipes / tunnels across the Hayward fault have been about $74,000,000. The utilities currently have design efforts and future planned construction efforts over the next decade that will amount to an additional $69,000,000 (in $2008). These costs exclude other seismic retrofits due to ground shaking, landslide or liquefaction hazards, or the installation of new pipes for redundancy (more than $1 billion for the period 1990 through 2020).

If the implementation goes forward as planned, then by the year 2020, the majority of the seismically upgraded pipes (about 10) will survive a Hayward M 6.7 to 7.2 event; and that the utilities will be in a better position than they were in 1990 to respond to residual damage for the non-retrofitted pipes. Even after the year 2020 and the expenditure of some $140,000,000 for fault offset upgrades, hundreds of water pipes (most of them 12 inch diameter or smaller) will still suffer damage when exposed to 3 to 5 feet of fault offset. The solution to these remaining non-retrofitted pipes is a combination of long term replacement (100+ years) using seismic design requirements for new pipes; or good post-earthquake response capability to rapidly repair the pipes.

BACKGROUND

Several utilities have pipes and other infrastructure that cross the Hayward fault. These utilities (and approximate quantity of fault crossings) are: EBMUD (water, 200 pipes, 2 tunnels), City of Hayward Water Department (40 pipes), Alameda County Water District (110 pipes), San Francisco Public Utilities Commission (water, 4 pipes), Castro Valley Sanitary District (sanitary sewer, 1 pipe), Bay Area Rapid Transit District (2 tunnels, 2 at-grade tracks), and Pacific Gas and Electric (2 buried high voltage circuits). If one were also to include buried sanitary and storm sewer pipes, lower voltage power distribution circuits, cable TV, copper and fiber communication cables, natural gas distribution and transmission pipes, then the total number of potentially vulnerable buried pipes that cross the Hayward fault would approach more than 1,500.

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Figure 1 shows a 30-inch diameter EBMUD water pipe leaking where it crosses the Hayward fault near the Oakland Zoo. The water jetting out of the pipe is at a location where this same pipe had been previously repaired. When this pipe last failed, it was repaired quickly to restore water service, but the repair did not make the pipe "fault tolerant".

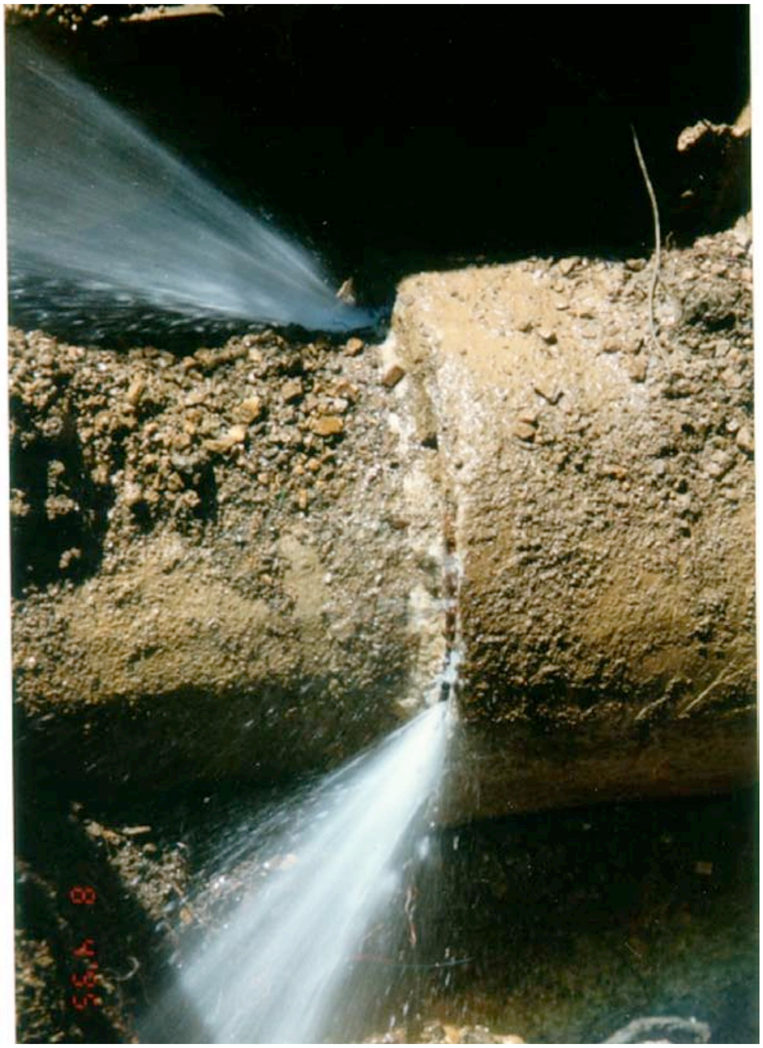

Figure 1. Leaking 30-inch diameter water pipe, damaged due to fault creep on the Hayward fault

Over the past 50+ years, EBMUD has maintained a record of every leak to their pipes, and there have been dozens of pipe failures (for pipes 20-inch and larger) due to ongoing fault creep. Figure 2 shows the number of times that EBMUD has repaired its 25 largest diameter water pipes where they cross the Hayward fault. All these pipes are welded steel, designed to AWWA M11 (or similar). The historical failure rate for these 25 pipes is about 1 to 2 per year due to fault creep. Figure 2 shows that some pipes fail much more often than others, and this depends largely on the local creep rate; the orientation of the pipe to the fault angle; the presence of nearby pipe appurtenances (like valves); and other factors.

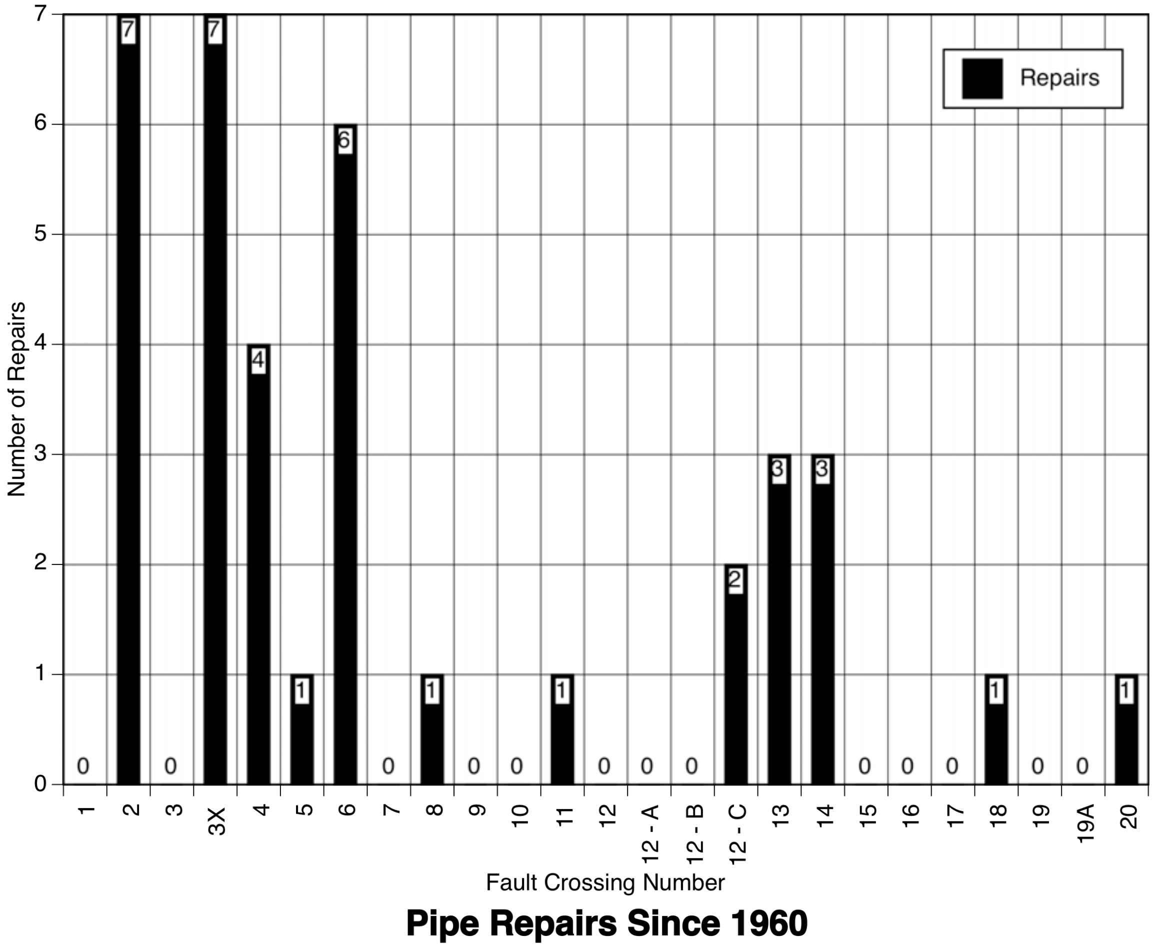

Figure 2. Leak history for twenty-five 20-inch and larger water pipes (EBMUD) due to ongoing Hayward fault creep, 1960-1990

Figure 3 shows SFPUC's Bay Division Pipelines (BDPL) 1 and 2 pipes (original construction) where they cross the Hayward fault in Fremont. BDPL 1 was built in 1923; BDPL 2 in 1933. These pipes were replaced in late 2002/early 2003 with new fault-tolerant pipes. The location of the creeping trace is shown in red. The effect of cumulative fault creep is clearly observed by the observed bend in the BDPL 2 (center of photo). Note that the bend in BDPL 2 is *not* at the fault location (the fault location shown is based on a trench dug 20 feet to the right); this is as expected given the strength of the pipe and the type of soil it is buried in.

Figure 3. SFPUC BDPL 1 (left) and 2 (right) Pipes

SEISMIC UPGRADE EFFORTS

In almost every instance for these 1,500 fault crossings, the original pipeline / tunnel / cable was installed with no particular attention to the Hayward fault. All of these 1,500 facilities were installed post-1868, with the bulk being installed between 1950 and 1975. All of these utilities are active in assessing the performance of these pipes and in some cases, making modifications.

Over the past 20 years, EBMUD has constructed a new "fault tolerant" water tunnel (completion 2007, cost about $30 million). For two large pipelines (one 24-inch and one 60-inch), EBMUD has installed new parallel High Density Polyethylene (HDPE) 24-inch diameter pipelines, to be used if the existing pipes break (after one HDPE pipe was installed, the adjacent 60-inch steel pipeline leaked due to ongoing fault creep). For several other 20-inch to 42-inch pipes, EBMUD installed valves either side of the fault, and installed bypass manifolds to allow restoration of water flow using ultra larger diameter (12-inch) flex hose, to be installed within the first several hours (to a day or so) after the earthquake.

The SFPUC has seismically upgraded BDPL 1 (60-inch) and BDPL 2 (66-inch) diameter water pipes by replacing them with new pipes that are designed to accommodate 5 feet of fault offset (constructed in 2003). At this location (see Figure 3), SFPUC also installed valves and bypass manifolds to allow the installation of six flex hoses to bypass the new 60-inch and 66-inch pipes should they unexpectedly fail. The SFPUC is currently designing upgrades for two other existing pipes (BDPL 3, 78-inch and BDPL 4, 96-inch), and construction of the first phase was completed in 2008 (isolation valves). Construction of a new BDPL 5 (72-inch) pipe that is designed to accommodate 5.5 feet of fault offset should begin in late 2009.

The City of Hayward water department has seismically retrofitted a 24-inch and 16-inch pipe to accommodate fault offset without damage, and three new 12-inch pipes are being installed, each designed to accommodate a few feet of fault offset without failure of the pressure boundary. This is a more aggressive pipe fault upgrade program as compared to EBMUD. The two utilities have taken different approaches, both with the same intent to restore service to some acceptable and cost effective level, but with different capital cost implications.

The Castro Valley Sanitary District collects raw sewage via a series of collection pipes. The collection pipes come together into one 36-inch diameter vitrified clay pipe (VCP). This VCP crosses the Hayward fault en route to a wastewater treatment plant. This 36-inch VCP was originally installed in a relatively deep trench (about 10 feet of cover) where it crosses the fault, with no special provision for fault offset. The sidewalk curb atop this pipe is offset by 8 inches due to ongoing fault creep, and the curb was built at the same time as the pipe. The utility ran a video camera through the pipe in 2007 to see how it was performing due to this ongoing creep, and the observations were a surprise: no visible cracks or joint movements in the VCP.

The Alameda County Water District has over 100 water pipes that cross the fault. Two of these (42-inch and 48-inch) were originally designed to accommodate ongoing creep or minor fault offset movements. One large steel pipe pulled apart due to fault creep in early 2008, as a reminder of the weakness in water pipes designed per AWWA M11. AWWA is the authority for water pipe design in the United States; through mid-2008, AWWA's "standards for pipes" do not have requirements for seismic design for fault offset, ground shaking, liquefaction or landslide. ALA (2005) is a guideline that can be used for design of water pipes that cross faults (as well as liquefaction, landslide and ground shaking). ACWD is contemplating a pipe upgrade program including various upgrades for large diameter pipes at fault crossings.

PG&E has two buried 115 kV transmission lines that cross the fault. Each transmission line consists of three copper-core cables within a steel pipe. The annulus between the cables and the inside of the pipe is filled with nitrogen gas. The lines can suffer damage (electrical "faults" or short circuits) if the protective pipe enclosure has its pressure boundary breached. PG&E's high voltage network provides some redundancy should these lines be damaged.

BART has two tunnels that cross the Hayward fault. The tracks within can take only a limited amount of movement due to ongoing creep. Within the tunnels are also fire water pipes, medium voltage power lines and various power and communication cables that cross the fault. BART is currently upgrading its rail system such that BART will be able to operate its transit system from the Rockridge station (west of fault) towards the west, and Orinda station (east of fault) towards the east, while using a "bus bridge" between Rockridge and Orinda while repairs are made to the tunnels, as needed. The at-grade track crossings near Castro Valley will need to be repaired if excessive fault offset occurs. There is no plan to make these tracks "fault tolerant".

VULNERABILITY ASSESSMENTS

Before these utilities and lifeline operators embarked on seismic upgrade of pipes or tunnels, they conducted seismic vulnerability assessments. To the extent that damage to the utility systems was shown to not excessively impact end users or create undue life safety impacts, damage to the pipes and tunnels crossing the fault was often found to be acceptable, with allowance that repairs would be made post-earthquake. It is when the outage time caused by pipe / tunnel failure is so long, and the economic consequences so severe, that the utilities have adopted seismic mitigation (fix the pipe so that it does not break) or install above ground hose capability by valving out the pipe and then installing above ground hoses to restore service within a few hours (or so) after the earthquake.

The seismic upgrade process has usually included the following steps. First, a system-wide evaluation was performed for the as-is utility system, to forecast damage and restoration times, considering redundancy and repair capability. This step usually included geologic hazard assessments that rely on available USGS (or other) hazard maps, including the 1992/2006 Lienkaemper maps of the Hayward fault. Second, the utility may have performed benefit-cost analyses to establish the optimal level of seismic upgrade for the system as a whole, and then selected a seismic upgrade plan and cost that satisfies (more or less) all of the following criteria: the net present value of benefits of the upgraded system outweigh the initial capital costs; the managers of the utility can implement the seismic upgrades within context of their overall capital improvement program; the upgrades meet a set of performance goals; the Board of Directors is comfortable with the rate increases that might be needed to support the seismic upgrades; the public are willing to pay. Third, for the selected seismic upgrade program, the utility often then performed more detailed site-specific geologic, geotechnical and pipeline engineering studies to optimize the design of the retrofit. For the very largest and most important pipes, new trenches were dug to help characterize the location of the fault strands, and their nature of offset. The evidence in nearby trenches that were used by developers for Alquist-Priolo purposes, often to show locations of "no fault", were assessed (or re-assessed), as the pipe "must" cross the fault someplace. For the largest pipes, the utility sometime inspected the inside of the old pipe to observe creep-induced damage, to help evaluate the capacity of the existing pipe as well as locate the fault.

DESIGN ISSUES

When performing interior pipe inspections, unsuspecting observers sometimes use the damage pattern of the pipe (or tunnel) to locate the fault, but often this leads to incorrect characterization, as the observer might draw a "primary offset zone" as wide (or a bit wider) than the zone of pipe deformation, while ignoring strength of materials and the pipe-soil interactions that places the creep / offset location *not* where the pipe damage is, but in-between the pipe damage locations. Different geologic specialists from different consultancies might produce reports for the exact same fault location, where one specialist states that the primary offset zone is 10 feet wide, and the other states that the primary offset zone is 70 feet wide, using the same trench and creep deformation information. From the design engineer's perspective, the wider the fault zone, the higher the construction cost. A simplified "standardized" method to convert observed creep damage on continuous or segmented pipes, as to how that relates to the location and amount of fault offset, would be a valuable tool to increase the quality of the overall design process and to reduce unnecessary construction costs.

The author has observed fault crossing designs that rely strictly on the location of straight lines in maps, which ignore zones of deformation and strength of mechanics principles, leading to what might be poor pipeline designs. For better design, the uncertainty in fault location (possibly one or multiple strands) and strike direction of the fault should be considered.

It is the collective opinion of several pipe designers that buried "ball and slip joint" installations are not satisfactory to accommodate 3 to 5 feet of fault offset on the Hayward fault. If one were to use EBAA (or similar) ball-and-slip joint assemblies, then a suitable rattle space should be provided. If the ball joints are placed far enough apart, then the pipe in between must be shown capable of sustaining both fault offset and inertial loading.

During the course of construction, unexpected conditions can (and do) occur, such as finding a previously unknown buried utility in the way of the new pipe. For common pipeline installations, these "surprises" are usually accommodated by re-routing the new pipe to go around. However, for seismically designed pipes that must be able to take 3 to 5 feet (or more) of fault offset without failure of the pressure boundary, introduction of bends in the fault crossing zone will result in unwanted stress risers, leading to reduced capability to withstand fault offset; so the optimal solution is usually to re-route the other utility.

The quality control of construction is particularly important for pipes crossing a fault, and the owner should not necessarily expect good pipe performance if the quality of pipe construction is just good enough to maintain the pressure boundary under a leak test.

ASSESSMENT OF PERFORMANCE AND LONG TERM ACTION

For the period between 1990 and 2008, costs for the above-mentioned utilities for seismic retrofit of existing pipes / tunnels across the Hayward fault have been about $74,000,000. These same utilities currently have design efforts and future planned construction efforts over the next decade that will amount to (about) an additional $69,000,000 (in $2008). These costs exclude other seismic retrofits due to ground shaking, landslide or liquefaction hazards, or the installation of new pipes for redundancy (more than $1 billion for the period 1990 through 2020). Assuming that the implementation goes forward as planned, then by the year 2020, one could assume that the majority of the seismically upgraded pipes (about a dozen) will survive a Hayward M 6.7 to 7.2 event; and that the utilities will be in a better position than they were in 1990 to respond to residual damage for the non-retrofitted pipes.

Even after the year 2020 and the expenditure of some $140,000,000 for fault offset upgrades, hundreds of pipes (most of them 12 inch diameter or smaller) will still suffer damage when exposed to 3 to 5 feet of fault offset. The solution for these remaining non-retrofitted pipes is a combination of long term replacement (100+ years) using seismic design requirements for new pipes; or good post-earthquake response capability to rapidly repair the pipes.

If the Hayward fault were to rupture in the year 2015 (after most of the currently-planned upgrades are completed), then there will still be about many hundreds of broken buried pipes across the Hayward fault. Should the event be a M 7.2 (or so) that ruptures the fault from end-to-end, with 3 to 5 feet of offset at all locations, perhaps 95% or more of all pipes (about 1,500) will break. Hopefully, society will manage reasonably well with the intact 5%, but certainly there will be outages and complaints and economic impacts. Over the next hundred years (or so), the utilities will eventually replace most of the 95% of the non-retrofitted pipes; ideally, the new replacement pipes will be designed to accommodate fault offset.

The Hayward fault also goes through some buried gasoline tanks and their pipes. Ground rupture plus a spark can lead to ignition and fire. Given the concurrent loss of water supply, fire spread cannot be ruled out. The Alquist Priolo Act contains rules to prevent structures for human habitation from being built across the Hayward fault without suitable mitigation. However, the Act does not apply to buried pipes or buried tanks. Today (2009), what is needed is a continued effort by all utilities to upgrade or replace their pipes with those with fault tolerant designs. It is uncertain if mandated legislation is needed to spur this activity, or just wait until the existing pipes reach their service life.

REFERENCES

ALA, 2005, Seismic Guidelines for Water Pipelines, American Lifelines Alliance, NIBS and FEMA, March 2005. http://www.americanlifelinesalliance.org/Products.htm#Guidelines