

Water Supply Damage, Recovery, and Lifeline Interaction in an Earthquake Sequence

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ABSTRACT

Earthquake damage to water supply systems profoundly affects society, potentially costing the economy tens of billions of dollars. Water agencies for 22% of the US population face high seismic risks. Computer models can help operators manage that risk. In recent research, the University of Colorado (CU) developed a stochastic model of water-supply pipeline damage and restoration. It offers some new capabilities: time-varying repair resources, multiple earthquake perils, lifeline interaction, avoiding hydraulic analysis, and no black-box software. CU exercised the model for the East Bay Municipal Utility District (EBMUD) and the San Jose Water Company, considering a hypothetical large Hayward Fault earthquake. EBMUD staff peer reviewed the methodology and results and find them credible and consistent with past earthquakes. EBMUD is using the results as part of its resilience program. Possible uses include prioritizing additional hardening or redundancy, identifying repair priorities, estimating resource needs, and informing earthquake exercises.

INTRODUCTION

Damage to water supply systems profoundly affects society after earthquakes. Large urban earthquakes can heavily damage buried pipeline networks. For example, the April 18, 1906 San Francisco earthquake caused 30 breaks in 85 km of large-diameter wrought-iron and cast-iron trunk lines, which led to the loss of water supply in the Mission District and the loss of water pressure to fight fires (Scawthorn et al. 2006). The October 17, 1989 Loma Prieta earthquake broke at least 761 water mains throughout the San Francisco Bay Area (Lund and Schiff 1991). The February 22, 2011 and June 13, 2011 Christchurch earthquakes caused 2,051 water pipe breaks and leaks (O'Rourke et al. 2014). The damage left 34% of households without water for more than a week and 5% for more than a month (Stevenson et al. 2011). Service providers can suffer enormous costs. The loss of water service can produce business interruption losses to the broader economy that dwarf service provider's repair costs. Rose et al. (2011) estimate that a hypothetical moment magnitude (M_w) 7.8 earthquake on the San Andreas Fault in Southern California could lead to \$50 billion in business interruption losses, in addition to the \$1 billion in pipeline repair costs.

Water agencies in 26 US states face similarly high risks (Figure 1). Approximately 22% of the US population lives in at least moderately high seismic hazard. Any of these water agencies might suddenly have to repair thousands of pipeline breaks and leaks, tens of thousands of broken service connections, in an environment lacking electricity, cellular communication, and functioning gas stations, amidst widespread building damage and with high employee absenteeism as workers ensure their family's safety.

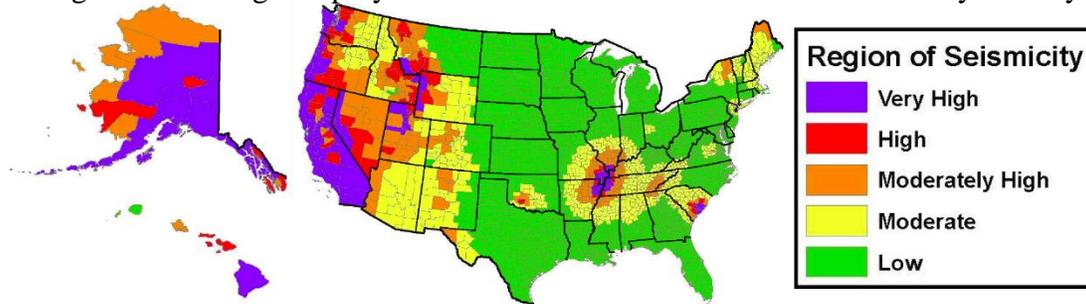


Figure 1. 22% of US water supply faces at least moderately high seismic hazard. (Image: public domain, from Applied Technology Council [2015])

For decades, engineers have developed computer models to help water service operators plan for earthquakes. Three examples: the GISALLE system proved that computer models can estimate pipeline damage and the hydraulic performance of the damaged system (e.g., Khater et al. 1989). MAEViz can treat damage to interdependent lifelines with system-of-systems analysis (e.g., Kim et al. 2007). Tabucchi et al.'s (2010) model simulates repair activities and estimates number of customers receiving service versus time.

There is need for a system with a combination of several attributes. We describe a new model designed to meet these goals: Model stochastic pipeline damage. Treat all earth-science perils throughout an earthquake sequence. Deal with time-varying lifeline interaction, human agency, repair crew availability, and availability of fuel and repair materials. Avoid the formidable data demands of a system-of-systems model. Avoid the need for hydraulic analysis. Quantify damage and restoration over time. Estimate impacts of water-supply damage to the regional economy. Model benefits of various resilience options. Use only a geographic information system and a spreadsheet. Such a model was developed for the U.S. Geological Survey's (USGS) HayWired earthquake planning scenario. We describe the model and offer a case study using the scenario and East Bay Municipal Utility District's (EBMUD) water distribution system. The new model requires the following input data:

- *Asset data*: map of pipes, material, diameter, and joints. If the network is divided among pressure zones or independent parts, identify the zone for each pipe. Currently the model only considers buried pipe, since they dominate repairs.
- *Hazard data*: mainshock and aftershock locations, dates and times; maps of peak ground velocity (PGV), liquefaction probability (PQ), landslide probability (PS), coseismic slip (CS) and afterslip (AS) at the ground surface.

- *Resource data*: time series of number of repair crews; fraction of repair-equipment fuel demand availability; probability that electric service is available at any arbitrary location; and similar probabilities vs. time for cellular communication, repair supplies (clamps, pipe, etc.), and other lifelines required to effect repairs.
- *Repair costs*: hourly labor cost of one repair crew, and time and material repair costs (large-diameter vs. small-diameter; break vs. leak).
- *Economic parameters*: gross state product (purchasing power parity) per capita per year (*GDP*); number of service connections in the service area (*M*); number of people served (*P*).
- *Resilience options*: what-if versions of the asset and resource data, such as after accelerated pipe replacement, or with emergency fuel supplies.

The model aims to produce the following outputs, under as-is and what-if conditions:

- *Damage locations and quantities*: Stochastic simulation of breaks and leaks.
- *Repair and service restoration timelines*: Number of repairs remaining and customers receiving service as a function of time. Optional stochastic simulation of repair time.
- *Performance outputs*: Customer-average and total number of service-days without water, and associated economic loss.

A NEW WATER NETWORK RESILIENCE MODEL

CU's new water network resilience model produces the aforementioned outputs using the aforementioned inputs. The new model has four analytical stages, named asset analysis, hazard analysis, damage analysis, and restoration analysis, detailed next.

Asset analysis. Depict the assets exposed to damage. Use a GIS to determine latitude, longitude, length, material, joint type, and diameter of each pipe segment.

Hazard analysis. Overlay asset and hazard data in GIS. For each pipe segment, determine PGV, PQ, PS, and CS in the mainshock and each aftershock.

Damage analysis. For each pipe segment and each earthquake, calculate the expected (average) number of repairs required \bar{R} , including breaks \bar{B} and leaks \bar{K} , using:

$$\bar{R}_w = (1 - P_L) \cdot (K_1 \cdot 0.01188 \cdot PGV) \cdot L \quad (1)$$

$$\bar{R}_l(P_L) = 8.07 \cdot K_2 \cdot P_L \cdot L \quad (2)$$

$$\begin{aligned} \bar{R}_s &= 2 && \text{if CS} > 15 \text{ cm} \\ &= 0 && \text{otherwise} \end{aligned} \quad (3)$$

$$\bar{R} = \bar{R}_w + \bar{R}_l + \bar{R}_s \quad (4)$$

$$\bar{B} = 0.15 \cdot \bar{R}_w + 0.5 \cdot \bar{R}_l + \bar{R}_s \quad (5)$$

$$\bar{K} = \bar{R} - \bar{B} \quad (6)$$

where \bar{R}_w denotes breaks associated with wave passage, PGV is measured in cm/sec, P_L denotes probability liquefaction or landslide, L is the length of the pipe segment in kilometers, \bar{R}_l denotes breaks associated with liquefaction, and \bar{R}_s denotes breaks

associated with coseismic slip and afterslip. Coefficients K_1 and K_2 account for pipe material, joints, and pipe diameter. Table 1 shows sample values. Equation (2) gives pipe breaks solely as a function of liquefaction probability rather than peak ground displacement because break rate appears to be only weakly dependent on peak ground displacement. The factor of 2 in Equation (3) attempts to account for afterslip: it assumes that coseismic slip breaks the pipe, the utility repairs it, afterslip breaks it again, and the utility learns its lesson about afterslip.

Table 1. Sample values of vulnerability coefficients K_1 and K_2 (Eidinger 2001).

<i>Pipe material</i>	<i>Joint type</i>	<i>Diam.</i>	K_1	K_2
Cast iron	Cement	Small	1.0	1.0
Cast iron	Rubber gasket	Small	0.8	0.8
Welded steel	Lap arc welded	Small	0.6	0.15
Welded steel	Lap arc welded	Large	0.15	0.15
Asbestos cement	Cement	Small	1.0	1.0
PVC	Rubber gasket	Small	0.5	0.8
Ductile iron	Rubber gasket	Small	0.5	0.5

Equations (7) through (10) sum over earthquakes in the sequence to estimate total number of breaks (B) and leaks (K—unrelated to the coefficients K_1 and K_2 in Table 1) in large-diameter (subscript L) and small-diameter (subscript S) pipe. In these equations, “eqks” means sum over the earthquake sequence; “LDsegs” and “SDsegs” mean large-diameter or small-diameter pipe segments; “e” is an index to earthquakes in the sequence; and “i” is an index to pipe segments.

$$\bar{B}_L = \sum_{eqks} \sum_{LDsegs} \bar{B}_{e,i} \quad (7)$$

$$\bar{K}_L = \sum_{eqks} \sum_{LDsegs} \bar{K}_{e,i} \quad (8)$$

$$\bar{B}_S = \sum_{eqks} \sum_{SDsegs} \bar{B}_{e,i} \quad (9)$$

$$\bar{K}_S = \sum_{eqks} \sum_{SDsegs} \bar{K}_{e,i} \quad (10)$$

Restoration analysis. Equation (11) estimates the number of repairs in t days.

$$\begin{aligned}
 F(t) &= 0 & t < t_0 \\
 &= \frac{1}{d_0} \int_{t_0}^t w(t) c(t) \left(\prod_j 1 - u_j (1 - g_j(t)) \right) dt & t \geq t_0 \\
 &\leq \sum_{m=0}^{n(t)} \bar{R}_m
 \end{aligned} \quad (11)$$

where t_0 denotes the time in days after the earthquake when repairs begin, $w(t)$ denotes the fraction of a day that a crew works (e.g., 0.5 for 12 hours on, 12 off), $c(t)$ denotes the number of repair crews operating on day t , j is an index to factors that can slow repairs, such as limited fuel, electricity, cellular communication, etc., and u_j is a constant to indicate the reduction in repair productivity in the absence of resource j required to perform a repair. Variable m is an index to earthquakes and $n(t) + 1$ is the

number of earthquakes prior to time t . One assigns u_j by estimating the additional time required to carry out one repair without the required resource:

$$u = 1 - \frac{d_0}{d_{\text{impaired}}} \quad (12)$$

where d_0 is the average time required to perform a repair under normal conditions and d_{impaired} is the average time it takes to perform a repair when the required resource required is unavailable. For example, if a repair takes 8 hours normally, but 9 hours without a certain resource, $u = 1 - 8 \text{ hr}/9 \text{ hr} = 0.11$. That is, productivity drops by 11% in the absence of the resource. A larger u means more impact if the resource is slowed, and $u_j = 1.0$ means that without resource j , repairs stop. The quantity d_0 has been estimated empirically as 0.32 days to 0.82 days on average, depending on pipe size. The function $g_j(t)$ denotes the flow of rate-limiting factor j at time t , normalized so that $g_j(t) = 1.0$ indicates unlimited availability, $g_j(t) = 0.5$ indicates that the flow or supply rate of rate-limiting factor j is half of what is normally available, etc. If for example a utility can only fuel half its repair vehicles, its g -value is 0.5. In the case of a rate-limiting factor that is a lifeline with a total number of service connections M_j and a number of service connections available at time t denoted by $V_j(t)$, then

$$g_j(t) = \frac{V_j(t)}{M_j} \quad (13)$$

Number of services available at time t . Calculate V_0 , the initial number of services in a given pressure zone receiving water, and $V(t)$, services receiving water on day t :

$$V_0 = M \cdot \left(1 - \Phi \left(\frac{1}{b} \ln \left(\frac{\bar{R}}{L \cdot q} \right) \right) \right) \quad (14)$$

$$V(t) = V_0 + (M - V_0) \cdot \left(\frac{F(t)}{\bar{R}} \right)^a \quad (15)$$

Here, M denotes the number of services, \bar{R} is the number of repairs required, L is the length of pipe in kilometers, a is a constant (empirically, 0.67, based on restoration of water service after the 1994 Northridge and 1995 Kobe earthquakes), Φ is the standard normal cumulative distribution function, and q and b are constants with empirically derived values 0.1 and 0.85, respectively. Figure 2A and B illustrate equations (14) and (15), respectively. In Figure 2A, the x-axis measures \bar{R}/L (breaks per km of pipe); the y-axis, V_0 . In Figure 2B, the x-axis measures $F(t)/\bar{R}$ (fraction of repairs completed); the y-axis, $(V(t)-V_0)/(M-V_0)$ (fraction of service restoration completed).

Economic consequences of network damage. Equation (16) estimates the utility's cost to repair damage. Equation (17) estimates the cost to the local economy from water supply impairment. In Equation (16), C_{LB} , C_{SB} , C_{LK} , and C_{SK} are the average cost to repair large-diameter breaks, small-diameter breaks, large-diameter leaks, and small-diameter leaks, respectively. GDP is the per-capita state gross domestic product (purchasing power parity); P is the population served; M is the number of service connections; and T is number of days until the last repair.

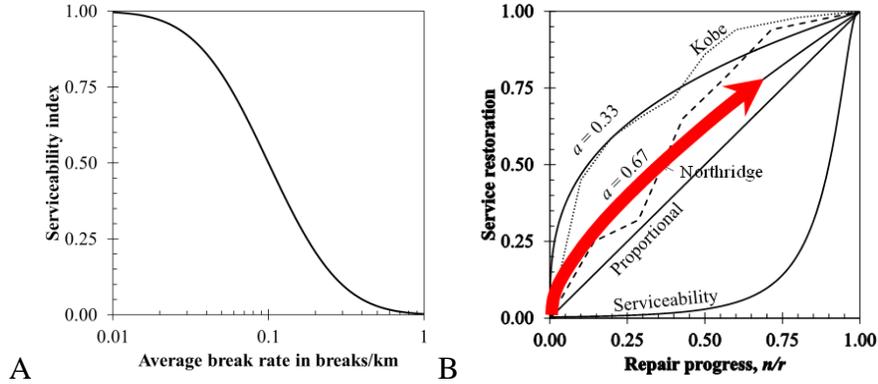


Figure 2. (A) Initial service V_0 as given breaks per kilometer of pipe. (B) Service restoration versus fraction of repairs completed

$$\bar{C}_U = \bar{B}_L \cdot C_{LB} + \bar{B}_S \cdot C_{SB} + \bar{K}_L \cdot C_{LK} + \bar{K}_S \cdot C_{SK} \quad (16)$$

$$\bar{C}_T = \left(\frac{GDP}{365} \cdot \frac{P}{M} \right) \int_{t=0}^T (M - V(t)) \cdot dt \quad (17)$$

Resilience options. The analyst can calculate damage and restoration over time under as-is and what-if conditions that may impact the ability of the water distribution system to withstand the event or the utility's recovery. What-if conditions examine resilience options, such as:

- *Reduce damage:* accelerate the replacement of brittle pipe.
- *Reduce reliance on gas stations:* install fueling systems with generator-powered pumps.
- *Reduce reliance on commercial electricity:* install emergency generators.
- *Reduce reliance on cellphones:* use radios to coordinate repairs.
- *Increase crews:* ensure that mutual assistance plans with other utilities will provide sufficient resources.
- *Reduce employee absenteeism:* help employees check their families' safety. Train employees to drop, cover, and hold on. Promote home preparedness.

CASE STUDY: HAYWIRED SCENARIO AND EBMUD WATER SYSTEM

HayWired is a product of the USGS Science Application for Risk Reduction (SAFRR) program. SAFRR aims to innovate the application of hazard science for the safety, security, and economic well-being of the nation. SAFRR produced the ShakeOut earthquake scenario (Jones et al. 2008), ARKStorm winter storm scenario (Porter et al. 2010), SAFRR Tsunami Scenario (Ross et al. 2013), and other materials that inform community resilience decisions. For example, ShakeOut inspired worldwide emergency preparedness exercises involving more than 50 million people and informed decisions to improve Los Angeles' water supply system, soft-story wood frame buildings, older concrete buildings, and cellphone infrastructure.

HayWired provides new information, such as insight into lifeline resilience, seismic performance of new buildings, urban search and rescue, earthquake early warning, and numerical simulation of ground motion. This paper presents a new scholarly model to estimate earthquake damage and restoration of water distribution systems. It illustrates the model using the HayWired earthquake sequence (M_w 7.0 mainshock and a realistic sequence of 16 aftershocks of M_w 5.0 or greater) as it affects EBMUD's water distribution system. Figure 3 shows a few aspects of the earthquake mainshock and EBMUD's system. EBMUD supplies water over 331 square miles, to 1.4 million people through 390,000 service connections, with 4,200 miles of pipe, a majority of which (59%) is relatively brittle cast iron or asbestos cement.

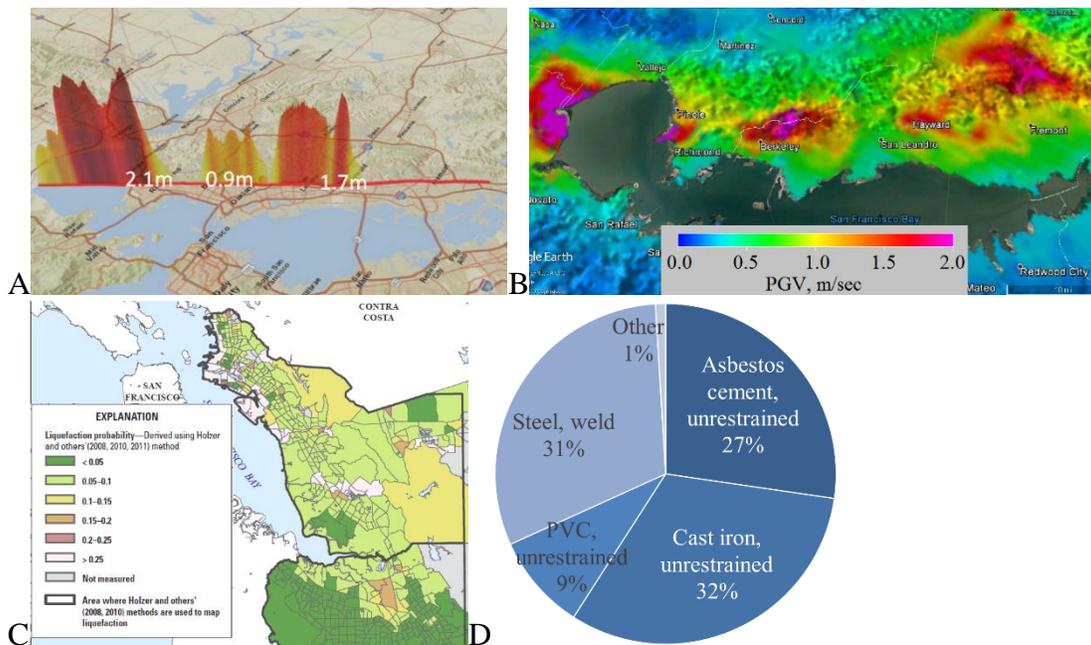


Figure 3. (A) Mainshock surface slip. (B) Mainshock PGV. (C) Liquefaction probability. (D) Pipe inventory.

The hypothetical mainshock occurs at 4:18 PM, Wed April 18, 2018, rupturing the north and south segments of the Hayward Fault in San Francisco Bay area. *This is a scenario, not a prediction. If such an earthquake happened, what outcomes could EBMUD reasonably expect, and how could it plan for and reduce undesirable consequences?* We start with the assumption (from Hazus and EBMUD judgment) that electricity takes 2 weeks to restore to critical facilities, fuel is limited for a week, and other utilities can send 15 crews under mutual assistance to bolster EBMUD's 20, for 1 month, as shown in Error! Reference source not found..

The earthquake sequence causes approximately 5,500 breaks and leaks, mostly in brittle pipe, softer soil, liquefaction-prone soil, and where the network is densest. It could take about 6 months to restore service. The timeline relies on a number of assumptions, e.g., that EBMUD would only accommodate an extra 15 repair crews through mutual assistance and for a relatively brief time (Figure 4C). EBMUD has

entered into mutual assistance agreements with large agencies outside the Bay Area who are not exposed to the same earthquakes and who could provide a significant number of crews to support recovery.

Damage would cost 19 million service-days (days to restore service times customers). The average customer loses service for 7 weeks. The damage costs the economy on the order of \$14 billion, ignoring fire losses. Resilience measures can reduce the economic loss by \$8 billion and restore service 4 weeks sooner, but at a high cost: replacing all of its cast iron and asbestos cement pipe would cost ratepayers \$6 billion (assuming a replacement cost of \$2.5 million per mile to replace 2,400 miles of cast iron and asbestos cement pipes). Implementing a fuel plan can save the economy \$200 million and restore water service an average of one day sooner.

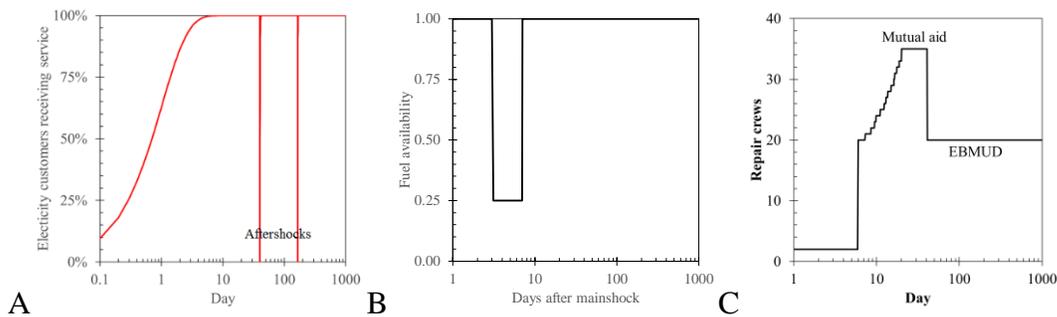


Figure 4. (A) Electricity, (B) fuel, and (C) repair crew availability

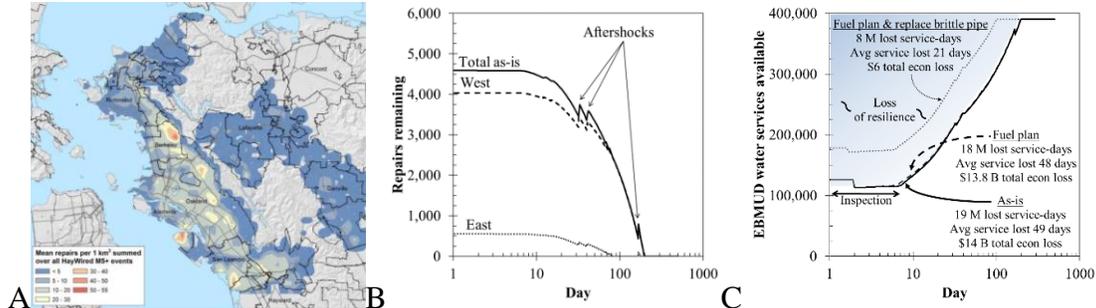


Figure 5. (A) EBMUD repairs/km². Warmest colors: 50+ repairs/km². (B) Repairs take 6 months. (C) Water supply interruption costs society \$14 billion.

IMPROVING RESILIENCY: EBMUD USES OF CU'S MODEL

Model predictions presented in this paper are generally consistent with prior studies and analyses completed as part of EBMUD's Seismic Improvement Program (SIP). As discussed above, the new CU model estimates over 4,600 leaks and breaks as a result of the main shock, with an additional 900 leaks and breaks as a result of aftershocks for a total of 5,500 leaks and breaks. Full restoration of EBMUD's water distribution system takes about six months. These estimates are consistent with results of EBMUD's 1994 SIP studies, which indicated that the extent of damage to distribution pipelines as a result of a Hayward M_w 7.0 earthquake would include more than 4,000 leaks and breaks, and that nearly 90% of the pipe damage would result from breaks in

cast iron and asbestos cement pipe, which account for nearly 60% of the distribution system.

EBMUD's 10-year \$189-million SIP included retrofit of facilities to minimize earthquake impacts on EBMUD's water system. The program, which was completed in 2007, included seismically upgrading 13 building structures, 70 storage reservoirs, 130 pumping plants, 5 water treatment plants, 56 pipeline fault crossings, 18 upgrades in areas of landslides and liquefaction, and 8 transmission system upgrades. The upgrades improve flexibility for transmitting water in the distribution system and mitigate landslide hazards for key pipes. It was, however, too costly to replace the nearly 1,300 miles of cast iron and 1,100 miles of asbestos cement pipes.

Since completion of its SIP, EBMUD has implemented a number of mitigation programs and resilience strategies. Working with numerous other agencies at the federal, state, and local levels, EBMUD has implemented institutional as well as physical infrastructure improvements. In 2016, EBMUD completed a local hazard mitigation plan (LHMP) in accordance with guidelines of the Federal Disaster Mitigation Act of 2000 (DMA 2000). This LHMP summarizes EBMUD's recent and upcoming system upgrades, improvements, and mitigation measures to reduce the community's exposure to hazards such as a HayWired M_w 7.0 earthquake. Highlights of some of the capital programs EBMUD implemented to improve the reliability, resilience, and robustness of its distribution system includes:

- ***Summit Transmission Pipeline:*** the Summit Pressure Zone (PZ) pipeline runs along the Hayward Fault. Creep has caused repeated leaks along this pipeline. As illustrated in Figure 5A, pipe damage is estimated to occur along the Hayward Fault in the City of Berkeley. The Summit PZ South Pipeline Project, currently in its planning phase, includes relocation of 3.6 miles of 24-inch transmission main in the cities of Berkeley and Oakland, to move the old water main out of the Hayward Fault Zone. Completion of this project will improve the resilience of this more vulnerable part of the system, and will allow EBMUD to restore services more quickly in this area after a major earthquake.
- ***Alameda Estuary Crossings:*** Alameda is uncommon in that it does not have storage facilities within city limits. It relies on several estuary crossings for water supply. CU's model confirms that these estuary crossings are particularly vulnerable to liquefaction damage. A study identified three crossings that should be replaced in the next 10 years to improve reliability. This project will improve the reliability of the main feeds to Alameda with new seismic-resistant transmission pipelines in areas prone to liquefaction.
- ***Large Diameter Pipeline Replacement Program:*** In 2012, EBMUD started replacing large-diameter mains at a rate of 3 miles per year. The program will gradually improve the reliability of transmission pipelines. In 2015, EBMUD completed the Dingee Pipeline and Claremont Center Aqueducts Replacements Project, which included replacement of over 3 miles of 24- to 54-inch diameter transmission pipelines in the cities of Oakland and Berkeley, which as shown in Figure 5A are susceptible to higher concentrations of breaks due to the type, age,

and proximity of pipes to the Hayward Fault. This project, which was the first of many capital projects as part of this new program and included replacement of an old transmission main outside of the Hayward fault zone, will significantly improve the seismic reliability of the water supply to large parts of Oakland and Berkeley, including 18,000 EBMUD customers in the central Oakland hills.

- **Pipeline Rebuild Program:** In 2014, EBMUD initiated a new program to gradually increase its rate of pipeline replacements from approximately 10 miles to a goal as high as 40 miles per year, equivalent to a rate of about 1% of the total length of buried distribution pipe per year. The program will gradually improve the robustness and resilience of EBMUD's distribution system to earthquakes, as it primarily focuses on the replacement of older and more brittle cast iron and asbestos cement pipes. These pipes account for a majority of EBMUD's breaks and leaks that are estimated to occur as a result of a HayWired M_w 7.0 earthquake. With 2,400 miles of cast iron and asbestos cement pipe, it will take on the order of 60 years to replace all of it at a rate of 40 miles per year. Since earthquakes happen on a geological timescale, it is possible that much of the brittle pipe will actually be replaced before an earthquake like the M_w 7.0 HayWired event occurs.

EBMUD's Water System Capital Improvement Program cash flow for Fiscal Year 2016 was \$231 million, and the total capital budget includes estimated cash flow spending of \$1.5 billion over the next five years. In addition to the pipeline renewal programs summarized above, which include \$258 million in capital investments over the next five years, highlights of EBMUD's CIP includes \$158 million for water treatment plant improvements, \$63 million for pumping plant improvements and \$102 million for reservoir improvements, including replacement of EBMUD open-cut reservoirs with modern seismically resistant reinforced concrete tanks. By gradually replacing its aging infrastructure, including replacement of old mechanical and electrical equipment, many of these capital projects will continue to further improve the seismic reliability and robustness of EBMUD's water treatment, storage, and distribution system.

Other planned transmission improvements include four transmission pipeline segments along the Hayward Fault, costing \$59 million over five years. These improvements will allow EBMUD to isolate and repair sections of an older parallel concrete cylinder pipeline, known as the Wildcat Aqueduct, which is expected to experience multiple joint leaks. The first phase of improvements, the Wildcat Pipeline in Berkeley, is shown in Figure 6 and includes installation of approximately one mile of parallel 48-inch diameter welded steel transmission pipeline (Ellsworth Street Alignment). These and other future improvements will improve the resilience of EBMUD's transmission system along the Hayward Fault.

Improving its modeling capabilities helps EBMUD to better prioritize and determine which parts of its infrastructure would benefit most from additional hardening. In addition to helping EBMUD determine how best to further improve the robustness to its distribution system, the HayWired study also helps EBMUD improve its emergency response plans including improved understanding of potential damage areas to help

prioritize repairs, determining resource needs and assumptions for pipeline repair crews, employee training, community outreach, and earthquake exercises. EBMUD is working with local communities to plan for prolonged water disruption, including:

- Phased emergency water distribution.
- Points of distribution (POD) for bottled water, tankers, or other alternative supply.
- Prioritized recovery for critical customers in advance of full system recovery.
- Participating in the HayWired Coalition to understand and reduce seismic risk.



Figure 6. Wildcat Transmission Pipeline.

EBMUD is also in the process of reaching out to hospitals in its service area, as one of its most critical customers, to share information about ongoing capital programs to improve seismic resiliency and to understand hospitals' water supply expectations and capabilities in the event of a significant earthquake. These emergency-preparedness discussions will help hospitals to improve their emergency water supply plans and to consider options for improving their water supply reliability.

CONCLUSIONS

A new water network restoration model calculates earthquake damage and recovery time, considering human agency, lifeline interaction, resource limitations, ground shaking and ground failure in an earthquake sequence, without requiring proprietary data or black-box software. It is illustrated here with a hypothetical earthquake sequence that begins with an M_w 7.0 rupture of the Hayward Fault in the San Francisco Bay Area, and the water network operated by EBMUD. Under as-is conditions, the earthquake sequence (the mainshock and 16 M_w 5.0+ aftershocks) causes 5,500 breaks and leaks that take 6 months to repair, costing the regional economy \$14 billion in business interruption losses, not counting losses associated with fire following earthquake. The damage and losses can be halved by replacing cast iron and asbestos cement pipes with ductile pipe before the earthquake occurs, but that process takes decades. Instead, like other large water agencies, EBMUD has implemented a number of mitigation programs and strategies to create a more disaster-resistant region and

utility system. These programs and strategies include capital programs to replace aging transmission mains at a rate of 3 miles per year; ramping up pipe replacement rate for distribution pipes to 40 miles per year (about 1% per year); and other programs to improve the reliability, resiliency, and robustness of its distribution system to large earthquakes such as a HayWired M_w 7.0 event.

REFERENCES CITED

- Jones, L.M., Bernknopf, R., Cox, D., Goltz, J., Hudnut, K., Mileti, D., Perry, S., Ponti, D., Porter, K., Reichle, M., Seligson, H., Shoaf, K., Treiman, J., and Wein, A. (2008). *The ShakeOut Scenario*. USGS OFR 2008-1150
- Khater, M.M., Grigoriu, M.D., and O'Rourke, T.D. (1989). "Serviceability measures and sensitivity factors for estimating seismic performance of water supply systems." *Proc 9th World Conf. on Earthquake Engineering, Tokyo Japan*, VII 123-128.
- Kim, Y.S., Spencer Jr, B.F., Song, J., Elnashai, A.S., and Stokes, T. (2007). *Seismic Performance Assessment of Interdependent Lifeline Systems*. MAE Center CD Rel. 07-16.
- Lund, L., and Schiff, A. (1991). *TCLÉE Pipeline Failure Database*, Technical Council on Lifeline Earthquake Engineering, ASCE, Reston VA, 36 pp.
- O'Rourke, T.D., Jeon, S.S., Toprak, S., Cubrinovski, M., Hughes, M., van Ballegooy, S., and Bouziou, D. (2014). "Earthquake response of underground pipeline networks in Christchurch, NZ." *Earthquake Spectra* 30 (1) 183-204
- Porter, K., Wein, A., Alpers, C., Baez, A., Barnard, P., Carter, J., Corsi, A., Costner, J., Cox, D., Das, T., Dettinger, M., Done, J., Eadie, C., Eymann, M., Ferris, J., Gunturi, P., Hughes, M., Jarrett, R., Johnson, L., Le-Griffin, H.D., Mitchell, D., Morman, S., Neiman, P., Olsen, A., Perry, S., Plumlee, G., Ralph, M., Reynolds, D., Rose, A., Schaefer, K., Serakos, J., Siembieda, W., Stock, J., Strong, J., Wing, I.S., Tang, A., Thomas, P., and Topping, K. (2010). *Overview of the ARkStorm Scenario*. USGS OFR 2010-1312, 183 pp., <http://pubs.usgs.gov/of/2010/1312/>
- Rose, A., Wei, D., and Wein, A. (2011). "Economic impacts of the ShakeOut scenario." *Earthquake Spectra*, 27 (2), 539-557.
- Scawthorn, C.R., O'Rourke, T.D., and Blackburn, F.T. (2006). "The 1906 San Francisco earthquake and fire." *Earthquake Spectra*. 22 (S2), S135-S138
- Stevenson, J.R., Kachali, H., Whitman, Z., Seville, E., Vargo, J., and Wilson, T. (2011). "Preliminary observations of the impacts the 22 February Christchurch Earthquake had on organisations and the economy." *Bulletin of the New Zealand Society for Earthquake Engineering*, 44 (2), 65.
- Tabucchi, T., Davidson, R., and Brink, S. (2010). "Simulation of post-earthquake water supply system restoration." *Civil Eng. and Environmental Systems*, 27 (4), 263-279