Cover page

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Author:
John M. Eidinger (Contact person)
President
G&E Engineering Systems Inc.
P.O. Box 3592
Olympic Valley, California, USA 96146-3592
Phone: (510) 595-9453
E-Mail: eidinger@geEngineeringSystems.com

Fragility Models that Reflect Pipe Damage in the Seismic 2014 Napa M 6.0 Earthquake

John M. Eidinger*

ABSTRACT

The City of Napa, California was struck by a M 6.0 earthquake on August 24, 2014. The water system, having 380 miles of pipe, underwent about 163 pipe repairs within two weeks after the earthquake. Of these pipe repairs, about 18 were due to surface faulting, 23 from liquefaction, and 122 from ground shaking. This rate of pipe damage, especially that due to ground shaking, is very high. This paper examines the reason(s) for this high repair rate due to ground shaking. We tested the soils in Napa, and found that much of the soils in the Napa area are extremely corrosive. Many of Napa's water pipelines are older cast iron pipes, but even newer thinner-wall ductile iron pipes had been failing due to non-earthquake-related reasons at a high rate prior to the earthquake. The results from the soil tests (as measured by Rho, in ohm-cm, at the depth of the pipeline) were correlated with observed long term water leak rates. There is good correlation with the inverse of Rho with repair rates for un-protected metal water pipes, such as older cast iron pipes, and unprotected ductile iron pipes. Given these findings, this paper suggests updated pipeline seismic fragility models for ground shaking that account for Rho, as measured in ohm-cm, as well as peak ground velocity, as measured in cm per sec.

* G&E Engineering Systems Inc., P.O. Box 3592, Olympic Valley, CA 96146-3592. Email: (eidinger@earthlink.net)

CITY OF NAPA WATER SYSTEM

The City of Napa was incorporated in 1872. The Napa Water Department serves a population of about 84,000 people, via 25,000 services. The water system includes 3 water treatment plants, about 542 km (337 miles) of pipe, 12 storage tanks with a total of 113.6 million liters (30 million gallons) storage, 9 pump stations, 14 pressure regulating stations and is operated in 5 pressure zones. About 90% of the populations is served by gravity flow coming from the water treatment plants.

Water demand peaks at about 95 million liters per day (95 m^3/day, 25 MGD) during a hot spell in July and drops to about 26 m^3/day (7 MGD) during the winter months. Landscape irrigation represents about half of yearly water demand. All potable water is provided from three surface water sources; no ground water is used. Of the total demand, about 53% is single family residential, 16% is multi-family residential, commercial is about 15%, institutional about 7%, landscape about 5%, St. Helena about 2%, agricultural about 1%, construction about 0.3%.

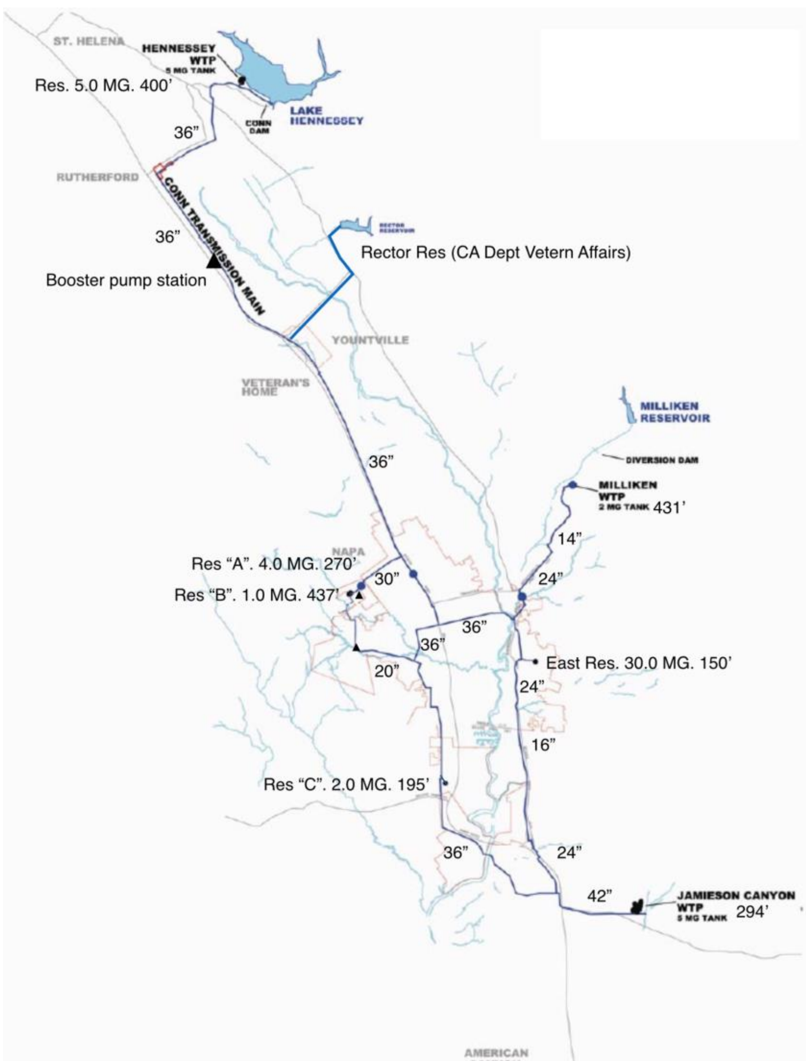

Figure 1. Napa Water System Major Pipelines and Location of Water Treatment Plants

As of September 30, 2014, Napa reported about 172 water pipe repairs. Through November 15, 2014, Napa reported 185 pipe repairs. Through late January 2015, Napa reported having completed 243 pipe repairs. By late January 2015, Napa reported that the repair rate for water pipes had reduced to "about" the long term average repair rate.

Table 1 lists the lengths of water pipes in the Napa water system (2012 data). Napa reports that in a typical year, there are about 80 to 100 pipe leaks in the city, system wide (about 0.21 to 0.26 repairs per mile per year). This leak rate for water pipes is consistent with industry average (about 0.24 to 0.27 leaks per mile per year). Other water departments in California with primarily cast iron pipe of similar vintages as in Napa (but with non-aggressive soils, Rho usually well over 5,000 ohm-cm) have system wide leak rates on the order of 0.06 leaks per mile per year. For example, the City of Burbank has zero pipe repairs in the 1994 Northridge earthquake, whereas neighboring Los Angeles had over 1,000 pipe repairs; both cities have similar-aged cast iron pipe, parts of both cities had similar levels of ground shaking, but Burbank's soils usually have higher Rho values than many parts of Los Angeles. This suggest that the rate of cast iron (and other metal pipe) pipe damage in earthquakes will tend to be relatively high, if Rho is low, or if the historical leak rate is high.

Age (years)	PVC	DI	CI	AC	RCCP	STL	Total	Pct of Total
< 20	6,600	225,600				100	232,300	13%
20-40	24300	370,500	83,400	14,100		100	492,400	28%
40-60		12,300	466,700	167,200	9,900	59,800	715,900	40%
60-80			173,100			100,400	273,500	15%
80-100			55,100				55,100	3%
> 100			10,300				10,300	1%
Total	30,900	608,400	788,500	181,300	9,900	160,400	1,779,500	100%
	2%	34%	44%	10%	1%	9%	100%	

Table 1. Length of Water Pipe Mains – Napa (Feet)

Table 2 lists the number of repairs by pipe material. The total number of repairs (163) reflects the amount completed as of about September 15 2015, at which time water was restored to essentially all customers. As discussed above, for several months afterward, the rate of pipe damage was about 2 to 3 times higher than normal: about 80 more repairs in about 4.5 months; whereas the long term rate was about 90 per 12 months.

This higher leak repair rate in the months following an earthquake is not unusual, reflecting that many pipes were highly stressed / deflected by the earthquake (but not immediately broken), but over time, these highly loaded pipes fail at a higher rate than normal. The City of Napa confirmed that the longer term pipe repair rate after the earthquake was higher than normal, with about an additional 50% of the immediate earthquake repairs (163) occurring by about late January 2015; after which the leak rate seemed to have reduced to about the long term rate.

Material	Repairs	% Repairs	% Pipe	Repair per Mile
AC	8	5%	10%	0.23
PVC	2	1%	2%	0.34
CI	123	75%	44%	0.82
DI	18	11%	34%	0.16
Steel	3	2%	9%	0.10
Other / unknown	7	4%		
Total	163	100%		

Table 2. Repair Rates for Water Pipe

Table 2 shows that CI (cast iron) is the most vulnerable of pipe materials, with AC (asbestos cement), PVC (polyvinyl chloride, C900), DI (ductile iron) and Steel (with corrosion protection) all performing much better than Cast Iron. Further examination of the repairs to correlate against location, in terms of peak ground velocity (PGV) and permanent ground deformation (PGD) and age (especially with respect to corrosion) is done later in this paper.

Figure 2 shows the level of ground shaking in the earthquake (in PGA, g), along with names of major cities and towns, and latest census populations shown in (brackets). The star shows the epicenter, with the rupture going northwards. Red areas show PGA > 0.7g. White areas show PGA < 0.05g. Black lines show boundaries of counties.

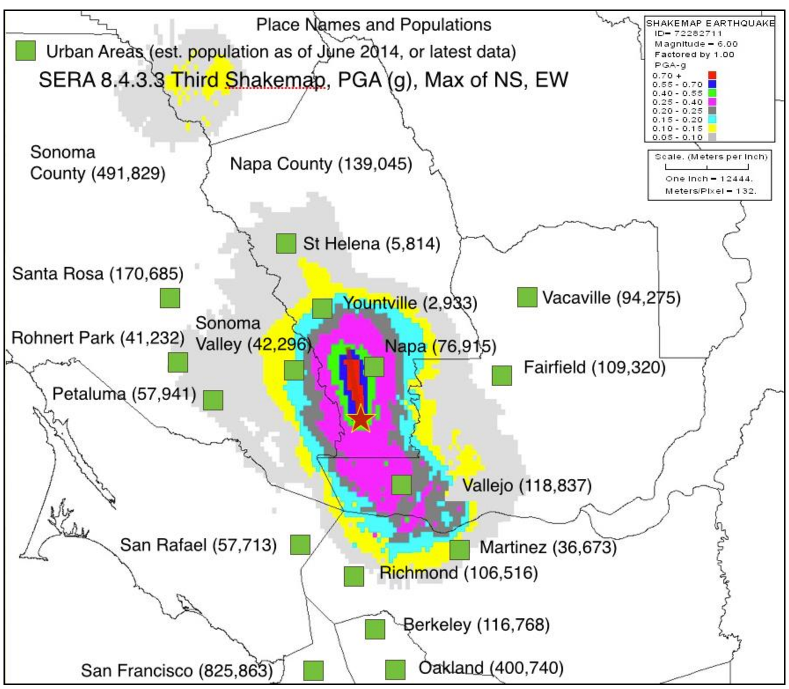

Figure 2. Ground shaking levels (PGA) on the Napa 2014 M 6.0 earthquake

Figure 3 shows the results from soil resistivity (Rho) tests performed in Napa after the earthquake. The locations of the Rho tests are indicated by small colored dots, and the actual test value at the depth of the water pipes (1.5 meters below grade is most common) is shown next to the symbol. The numbers in round circles are the highway numbers of major roads in and near Napa.

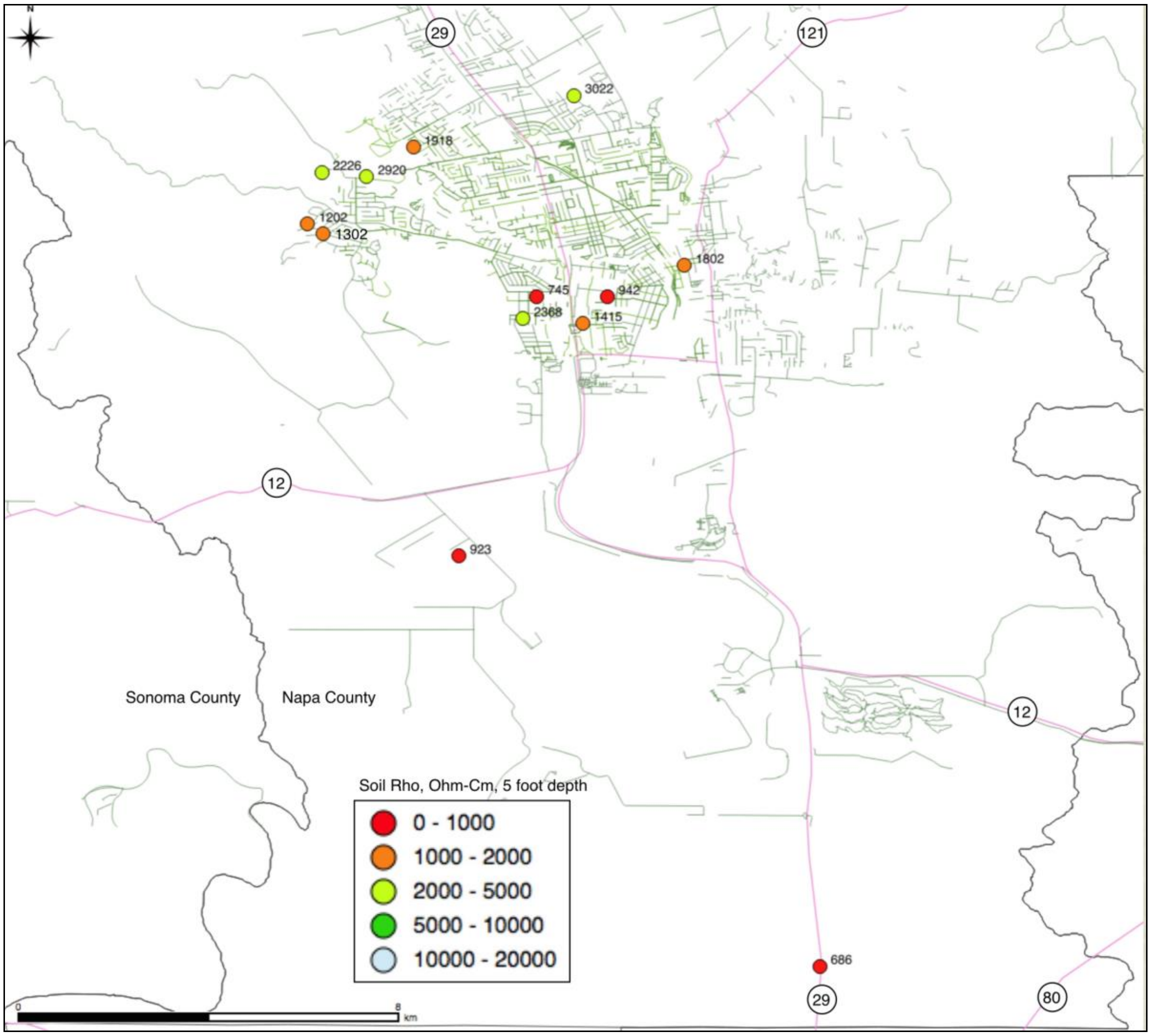

Figure 3. Soil Resistivity and Location of Pipe Repairs for Napa Water Pipe

Figure 3 shows that the soils in Napa are extremely aggressive. This may be in part due to the volcanic origins of the soils; many are clayey-in nature. At three test locations, Rho was under 1,000 ohm-cm (extremely corrosive); four more tests showed Rho from 1,000 to 2,000 ohm-cm (very aggressive); and four more tests showed Rho from 2,000 to 3,022 ohm-cm.

The Napa water department reports that their ductile iron pipe has had a fairly high leak rate, even without the earthquake, and this reflects that Napa apparently did not install polyethylene "baggies" over the ductile iron pipe. The very aggressive nature of the soils; coupled with the relatively thinner wall thickness of ductile iron pipe, under 0.5 cm (0.2 inches), relative older but thicker cast iron pipe that are commonly 1.27 cm (0.5 inches) or thicker.

In the northwest part of the water system, there was surface faulting. Figure 4 (left) shows a map of the 71 locations with observed surface faulting (yellow stars), along with the pipe repair locations. The light green lines indicate streets; light blue lines indicate major roads / highways.

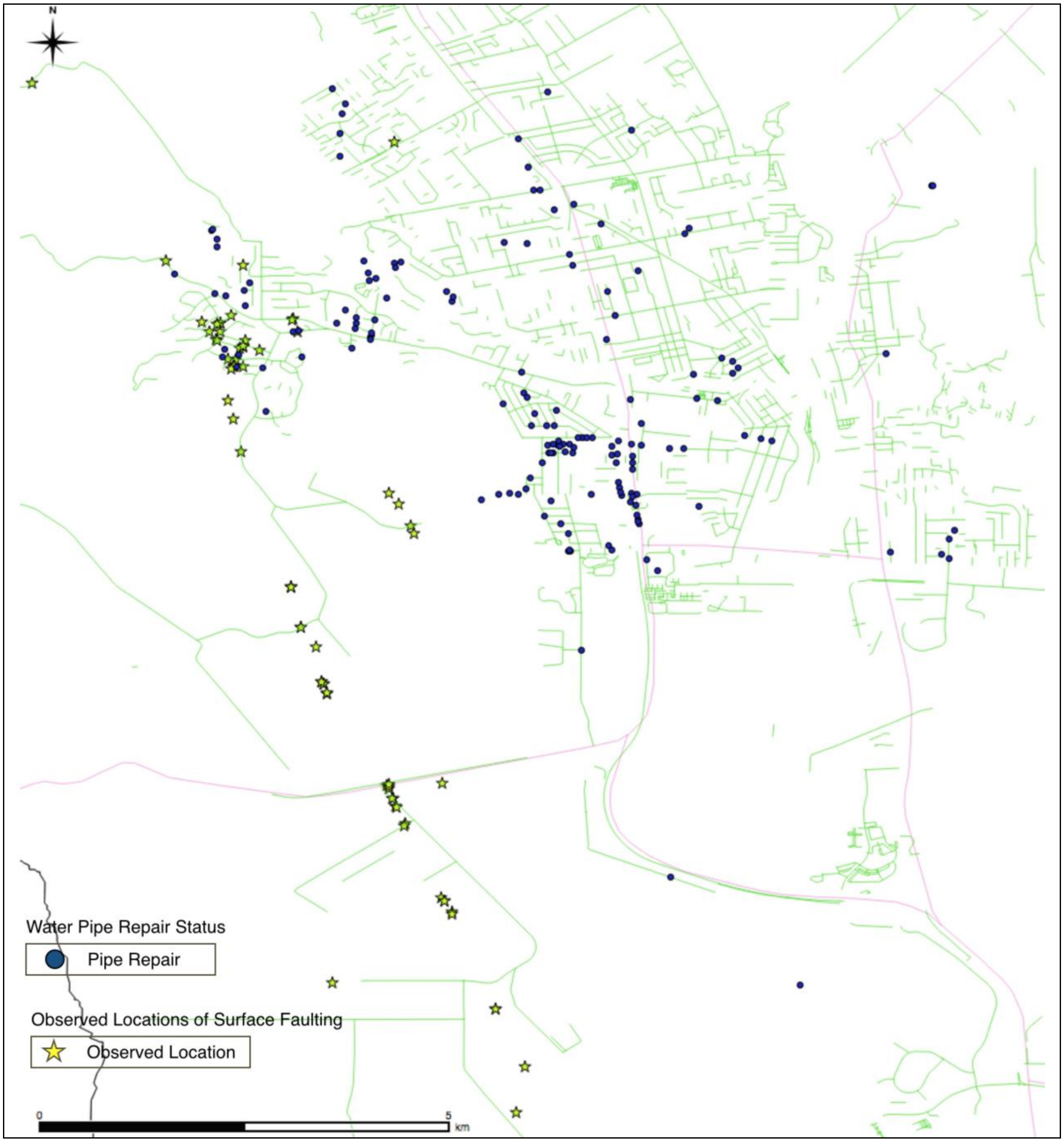

Figure 4. Location of Surface Faulting and Water Pipe Repairs

SEISMIC EVALUATION OF THE WATER PIPES

Figure 5 shows the Peak Ground Velocity (PGV) map for the Napa area due to the August 2014 earthquake. This map shows the maximum of north-south or east-west direction PGV. Each "box" represents an area of about 0.8 km (east-west) by 1 km (north-south). The symbols are at the locations of the pipe repairs as shown in Figure 4: solid dot: CI; triangle: DI; open dot = unknown; polygon: AC; square: PVC. The colors of the PGV shaking in Figure 5 correspond to: Red: PGV ≥ 85 cm/sec. Blue: PGV = 70 cm/sec to 85 cm/sec. Green: PGV = 55 cm/sec to 70 cm/sec. Magenta: PGV = 40 cm/sec to 55 cm/sec. Dark Grey: PGV = 30 cm/sec to 40 cm/sec. Cyan: PGV = 20 cm/sec to 30 cm/sec. Yellow: PGV = 10 cm/sec to 20 cm/sec

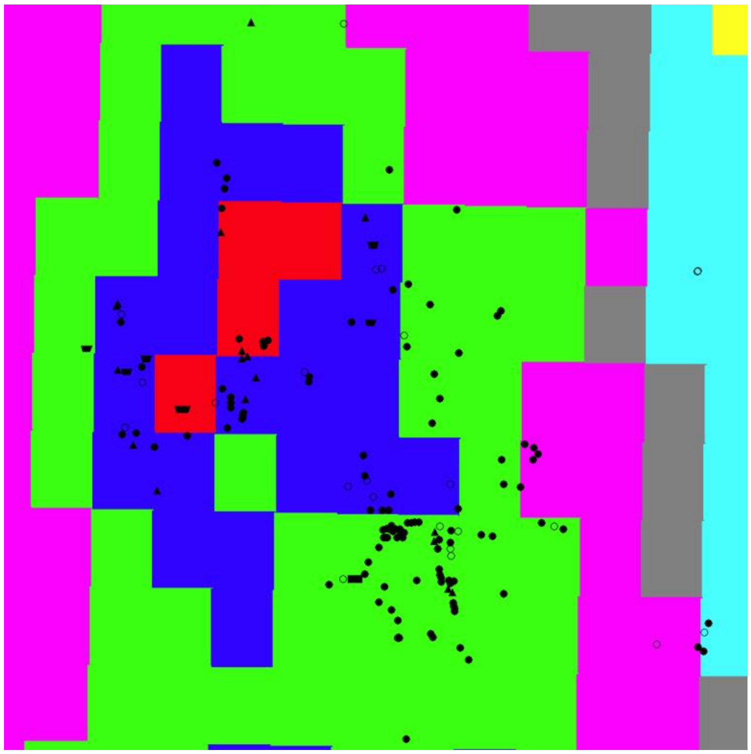

Figure 5. ShakeMap PGVs (Maximum of NS, EW)

Using the corresponding PGV ShakeMap levels of shaking from Figure 5, Table 3 shows the number of pipe repairs that were subjected to various levels of PGV (totals add to 164; 163 elsewhere in this report; the 1 pipe repair location had uncertain attribute as to whether there was 1 or 2 repairs at that location).

	20-30 cm/sec	30-40 cm/sec	40-50 cm/sec	50-60 cm/sec	60-70 cm/sec	70-80 cm/sec	80-90 cm/sec	Total
AC					2	2	3	7
CI	3		2	16	38	41	10	110
DI				2	4	4	7	17
PVC					2			2
STL					1	1		2
UNK	3	1	2	1	9	7	2	25
Total	7	1	4	19	56	55	22	164

Table 3. Water Pipe Repairs vs. PGV (cm/sec)

We reviewed the number of pipes that were located within about 152 meters (500 feet) from locations of surface faulting; and attributed that damage to surface faulting and not ground shaking or liquefaction effects. We also differentiated the number of pipes that were damaged due to liquefaction. Table 4 shows the results. The total number of pipes damaged from shaking was 122, with 23 repairs due to liquefaction, and 18 due to fault offset.

Pipe Type	Length, System-wide (miles)	Repairs due to Shaking (PGV)	Repairs due to Liquefaction (PGD)	Repairs due to Surface Faulting (PGD)	Total Repairs, August 24 to Sept 15 2014
AC	34.34	2	0	5	7
CI	149.34	86	19	5	110
DI	115.23	8	4	5	17
PVC	5.85	2	0	0	2
STL	30.38	2	0	0	2
RCCP	1.88	0	0	0	0
UNK		22	0	3	25
Total	337.01	122	23	18	163

Table 4. Water Pipe Repairs – PGV and PGD (faulting)

ALA (2001) provides pipe fragility models that factor in PGV and pipe material and diameter, but not the soil resistivity / corrosion effects. In Napa, the corrosion effects should be important, especially for Cast Iron and Ductile Iron pipes. We ran a forecast using modified ALA (2001) models, including the effects of corrosion, and the variations of ground shaking levels throughout Napa. The results are in Table 5.

Pipe Type	Length, System-wide (miles)	Actual Repairs due to Shaking	Forecast Repairs due to Shaking
AC	34.34	2	2.4
CI	149.34	86	88.5
DI	115.23	8	12.3
PVC	5.85	2	0.4
STL	30.38	2	5.0
RCCP	1.88	0	0.1
UNK		22	
Total	337.01	122	108.8

Table 5. Water Pipe Repairs – Forecast and Actual (due to PGV)

In preparing Table 5, the repair rate model for repairs due to shaking was assumed to be:

RR = k1 * k2 * k3 * 0.00187 * PGV, where

- RR = repairs per 1000 feet (305 meters) of pipe
- PGV = ground shaking, inches per second
- k1 = factor to account for corrosion (Table 6)
- k2 = factor to account for pipe diameter (Table 6)
- k3 = factor to account for pipe material (Table 6)

Pipe Type	This report k1 corrosion	This report k2 Diameter (≤ 12 inches)	This report k3 material	ALA 2001 Combined factor
AC	1.0	1.0	0.3	0.5
CI	1.0 to 3.0	1.0	1.0	1.0
DI	1.5	1.0	0.3	0.5
PVC	1.0	1.0	0.3	0.5
STL	1.0	1.0	0.7	0.7
RCCP	1.0	1.0	0.2	0.2

Table 6. Pipe Fragility Model due to Ground Shaking

Considering the situation in Napa, we suggest applying corrosion (k1) as follows for metal pipes:

- Rho < 1500 ohm-cm. Prior to 1920. k1 = 3.0. Post 1960. k1 = 1.0. 1920 to 1960, interpolate.
- Rho from 1500 to 2500 ohm-cm. Prior to 1920. k1 = 2.0. Post 1960. k1 = 1.0. 1920 to 1960, interpolate.
- Rho > 2500 ohm-cm. k1 = 1.0.

For ductile iron, asbestos cement and PVC, we suggest reducing the k3 factor from 0.5 to 0.3; this is in part offset by a corrosion factor, such that k1 * k3 is about the same as the combined factor in ALA

(2001). The main issues with shaking for these pipes is the pullout of joints, and all rubber gasketed pipes have similar joint pull out capabilities.

Based on the field observations in Napa we estimate the following lengths of pipe were subjected to liquefaction:

- Cast iron. 20,000 feet. Average PGD = 1 inch. Using the ALA (2001) models, this translates into a forecast total number of cast iron pipe repairs = 21.2.

- Ductile iron. 4,000 feet. Average PGD = 1 inch. Using the ALA (2001) models, this translates into a forecast total number of ductile iron repairs = 4.3.

Pipe Type	Length, System-wide (miles)	Actual Repairs due to Liquefaction	Forecast Repairs due to Liquefaction
AC	34.34		
CI	149.34	19	21.2
DI	115.23	4	4.3
PVC	5.85		
STL	30.38		
RCCP	1.88		
UNK			
Total	337.01	23	25.5

Table 7. Water Pipe Repairs – Forecast and Actual (due to Liquefaction PGDs)

NAPA WATER SYSTEM EMERGENCY RESPONSE

Figure 6 shows the restoration of water service after the earthquake.

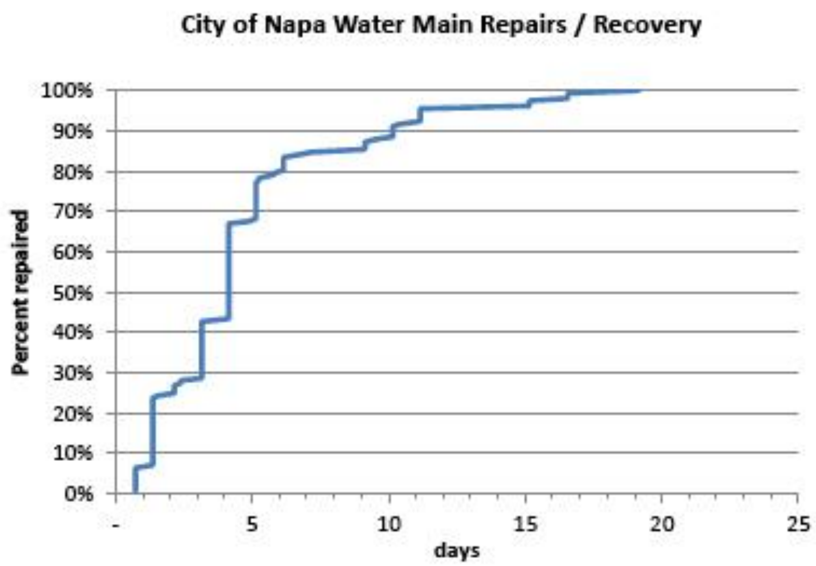

Figure 6. Napa Water Recovery

In making repairs, one of the required steps prior to digging up the area around the leaking pipe, is to perform "USA" markings (Underground Service Alert). This entails having each utility with underground facilities (gas, water, sewer, communications, etc.) to pre-mark the location of their pipes / conduits, prior to the commencement of digging to get to the leaking pipe. In the post-earthquake environment, when all utilities are also busy, this effort can slow down the entire restoration process. Following this process possibly slowed down the restoration effort for the water pipes. Still, the potential of accidently damaging a gas pipe, or otherwise damaging third party utilities, cannot be discounted, so this effort should be accounted for in emergency restoration plans.
Water demand increased by 200% or more immediately following the earthquake. This reflected normal overnight water demands, as well as water lost through leaking pipes, and some water being used for fire flows. As measured at the water treatment plants, the following water rates were recorded:

Time	Water Flows from WTPs	Then Known Water Leaks
Day 1. Sunday Aug 24	32 MGD	60 leaks
Day 2. Monday	28 MGD	90 leaks
Day 3. Tuesday	24 MGD	100 leaks
Day 4. Wednesday	22 MGD	105 leaks
Day 5. Thursday	20 MGD	110 leaks
Day 6. Friday	19 MGD	120 leaks
Day 20. Sept 12		167 leaks
Day 37. Oct 1		179 leaks
Day 68. Nov 1		193 leaks
Day 99. Dec 2		220 leaks
Day 153. Jan 26 2015		241 leaks

Table 8. Napa Water Flows, Million Gallons per Day, Number of Repaired Leaks

The average water demand for late August, without earthquakes is about 18 MGD. The actual water flows in the entire distribution system is uncertain, but in the first day would be much higher than the 32 MGD listed in Table 8, in that much of the water in the 12 storage tanks (with 30 MG capacity, mostly full at the time of the earthquake) also drained in the first few hours.

The Napa Water Department was aided by several regional utilities in making pipe repairs. Mutual aid (via Cal Warn) pipe crews were provided by:

- EBMUD: 5 crews. Three crews were initially dispatched within 24 hours of the earthquake, and two days later, two additional crews. EBMUD reports that the EBMUD crews helped make repairs for 56 pipe leaks.
- Contra Costa Water district: 1 crew
- City of Fairfield: 2 crews
- Alameda County Water District: 1 crew

All crews arrived with spare parts, trucks and equipment, typically 5 people per crew. All mutual aid crews were released by August 29 2014 (note the slow down in the rate of pipe repairs after Day 5, Figure 6). It was initially thought that the mutual aid crews were sufficient to effect nearly all the pipe repairs by August 29; however, over time, as the last pipe repairs were made, additional pipe leaks were identified as repaired pipes were re-pressurized.

The Napa Water Department estimated they spent about $200,000 on spare parts.

There were no regional-wide boil water alerts issued during or after the earthquake. Water quality at the water treatment plants was reported to be acceptable. The general population was encouraged to use bottled water (many did). There were boil water alerts to all customers who lost water supply, owing the concern of possible cross contamination from nearby potentially damaged sewer lines (no evidence that this occurred); or bacterial growth in empty water pipes.

The lack of a regional boil water alert was in part due to the negotiations between the Napa Water Department and other state-wide agencies. The state-wide agencies wanted a large scale boil water alert, being concerned that damaged sewer pipes might be leaking sewage into damaged water pipes. However, the City of Napa noted that they had no damage in the transmission pipes, and the water treatment plants were able to keep up with the increased water demand (for normal use lost water due to leaks, and fire fighting purposes), and positive pressure was maintained in the majority of the water system, so there was no need for such a regional boil water alert. Had the water transmission pipes been damaged, or the water treatment plants been unable to keep up with post-earthquake water demands, large portions of the water system would have become de-pressurized, and this would have had much more impacts on customers (more outages, boil water alerts, longer restoration times, etc.).

ACKNOWLEDGMENTS

The work reported in this paper was reviewed by Mr. Bruce Maison (EBMUD, Retired), and Prof. Mike O'Rourke (Rensselaer Polytechnic Institute). Mr. Maison and Prof. O'Rourke both participated in developing the ALA (2001) Water Pipeline Fragility report. Ms. Joy Eldredge, General Manager of the City of Napa City Water Department, provided pipe damage statistics.

REFERENCES

ALA, Seismic Fragilities for Water Systems, American Lifelines Alliance, March 2001.

SI UNITS

This paper uses both US customary and SI units of measure. The following are the conversions.

1" = 1 inch = 2.54 centimeters = 2.54 cm
1' = 1 foot = 0.3048 meters
1 mile = 1.609 kilometers = 1.609 km
1 MGD = 1 million gallons per day = 3,785,400 liters per day = 3,785.4 m^3/day.